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THESIS

**RAPID PROTOTYPING:
A SURVEY AND EVALUATION OF
METHODOLOGIES AND MODELS**

by

Harrison Douglas Fountain

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METHODOLOGIES AND MODELS

by
Harrison Douglas Fountain
Captain, United States Army
B.S.W., San Francisco State University, 1981

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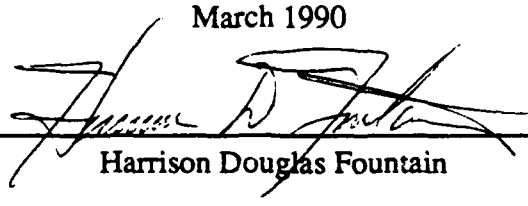
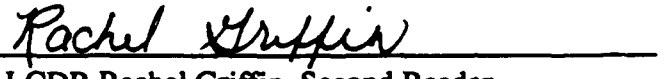
Author: 
Harrison Douglas Fountain

Approved By: 
Luqi, Thesis Advisor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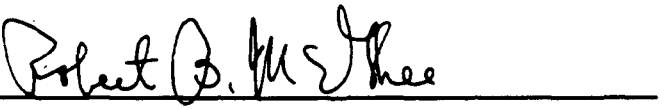
Robert B. McGhee, Chairman,
Department of Computer Science

ABSTRACT

The DoD requirements for software are growing almost as rapidly as the escalating cost of developing the software. The new rapid prototyping paradigm is an innovative approach to software development, which modifies the traditional life cycle model. This thesis features a comprehensive survey and evaluation of the rapid prototyping paradigm. The survey describes the rapid prototyping process, the complex prototyping support system environment required, proposed rapid prototyping methodologies, and published rapid prototyping models. The rapid prototyping methodologies and models are evaluated with respect to their conceptual design. The survey and evaluation of the methodologies and models reveal a progressive paradigm featuring some methodologies and models that can be implemented now and some that are capable of being implemented in the future. Because of DoD's influence on the software industry, we discuss how DoD should usher in the new paradigm, set strategic goals, and further decompose these goals into near-term, short-term, and long-term goals.

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I. INTRODUCTION

A. BACKGROUND

The recent and rapid advancements in computer technology, especially in computer hardware, have been a determinant factor in society's growing use of computer applications. During the 1980's, both the civilian sector and Department of Defense (DoD) found more complex processes which can be accomplished by computer technology. The civilian sector has advanced beyond using computers for only routine applications and is now using extensive automation in all echelons of industry. DoD has historically been interested in advancing and applying computer technology, as well as software application environments. DoD now uses computers to guide complex weapons systems, deploy and control satellites, execute the implementation of SDI, and manage intricate communications networks.

Advancements in computer hardware technology have led to increased processing speed and decreasing costs. The increase in the number of applications provided the impetus for increased software production and extensive research on how to efficiently develop software to meet the growing demand. As the hardware costs have decreased, software costs have increased dramatically. "In 1980 software cost approximately $40 billion, or two percent of the United States Gross National Product (GNP). The cost had increased to 8.5 percent of the GNP by the mid 1980's. It is predicted that the software costs will grow to 13 percent of the GNP by the early 1990's". [Ref. 1: p. 191] To combat the growing software costs, research funding for software engineering has increased. DoD has been very active in funding research,

primarily due to a strong commitment to bring escalating software costs back to a manageable state.

In the early 1980's, the majority of software engineering research funding was dedicated to evaluating and modifying the Waterfall Life Cycle Model. The advances in computer technology, and futile attempts to correct perennial requirements engineering problems led many researchers to investigate prototyping as a viable alternative to the conventional method of software development. By the mid 1980's, it was evident that the traditional (Waterfall) life cycle model was insufficient to meet future software engineering requirements. Any efforts to repair or refine the traditional model was comparable to placing a bandage on an ever-expanding wound. Recently there has been significant research published concerning rapid prototyping methodologies, computer-aided software engineering (CASE), and the utilization of reusable software components.

1. Software Engineering

"Software engineering is the application of science and mathematics (specifically algorithms) by which the capabilities of computers are made useful through the application of computer software programs, procedures, and related documentation". [Ref. 2: p. 2] A relatively new discipline, software engineering is primarily focused on devising techniques for software development. "Generally accepted goals for software engineering fall under the two related categories of system performance and design quality". [Ref. 2: p. 2] System performance is concerned with requirements engineering and ensuring that the delivered software accurately reflects the user's stated requirements. The quality of design is becoming more critical, primarily because of advanced hardware capabilities and cost constraints. The design issues that are of

primary interest are efficient use of resources, modularity, and understandable and maintainable code. "These goals are achievable by utilizing a modular architecture, localization of logically-related resources, uniformity of notation, accuracy of minimum required elements, and confirmability through the use of demonstrations". [Ref. 3: p. 30] The use of software life cycle methodologies is encouraged to provide structural and procedural means to the software development process. In some cases, the use of better software life cycle methodologies is required in order to meet restrictive software engineering goals.

2. Life Cycle Models

Software development is an evolutionary process. The process begins with the conception of a need for the software and ends with the retirement of the software. Life cycle models provide a methodical process for the development of software. "The primary functions of a life cycle model are to determine the order of the stages involved in software development and evolution and to establish the transition criteria of progressing from one stage to the next". [Ref. 4: p. 61] This process is considered essential in software development and acquisition, especially with respect to meeting both cost and completion deadlines.

The authors point out in [Ref. 1: p. 191] that software systems go through two principal phases during their life cycle, the development phase and the operations and maintenance phase. Development begins when the need for the product is identified. It ends when the implemented product is tested and delivered for use. Operation and maintenance include all activities during the operation of the software, such as fixing bugs discovered during operation, making performance enhancements, adapting the

system to its environment, adding minor features, etc. During this phase the system may also evolve as major functions are added.

"Software development methodologies have continuously evolved from the inception of the programmable computer. The evolution has been prompted by the perceived inapplicability of software development methodologies to the solution of increasingly complex problems". [Ref 5: p. 1453] Life cycle models generally are not originally designed as life cycle models, but rather as a process description of a specific methodology.

Given that methodologies are dependent on specific process applications, evaluation and comparison of models are difficult. "Alternative paradigms for development make comparisons difficult because concepts important to one model may not have any counterparts in another model based on a completely different paradigm". [Ref 6: p. 2] The lack of standards in formal definition and description of model design, concepts of implementation, and notation used often leads to misunderstood models. The vagueness of the models and the misunderstandings of those published unfortunately leads to the development of similar and at times identical models, only defined differently. "Another problem that surfaces is that experimental evaluation becomes impossible when actual development practices do not correspond to the models used to describe and analyze those processes". [Ref. 6: p. 2]

Another issue is that the software development and acquisition process is unmanageable. Given the cost constraints discussed earlier, along with developmental time completion constraints and changing technology, DoD needs a life cycle model that is generic enough to accommodate the software acquisition needs and specific

enough to meet the software development needs based on available and potential near-term computer technology.

Boehm describes in [Ref. 4: p. 63] that the first software development model that was recognized by the computer community was the Code-and-Fix Model. It contained basically two steps: 1) write some code, and 2) fix the problems in the code. The problems associated with this model were rapid decay of program structure, poor support for user's needs because of the lack of a requirements phase, and growing expense of the maintenance phase resulting from poor preparation for testing and modification. In 1956, the Step-wise Model was introduced. This model stipulated that software be developed in successive stages (operational plan, operational specifications, coding specifications, coding, parameter testing, assembly testing, shakedown, and system evaluation). This model was the precursor to the Waterfall Model, but was never instituted as a life cycle model in the software engineering community.

3. Waterfall Life Cycle Model

Software development prior to the 1970's was disastrous. The lack of a standard model prevented any logical management of software development. Progress in project development could not be tracked, production costs rose sharply, and rarely was software efficiently coded or error-free.

In 1970, Dr. Winston Royce introduced the Waterfall Life Cycle Model for software development [Ref. 5: p. 1454]. The Waterfall Life Cycle Model is reflected in Figure 1. This model brought the art of software development into the scientific realm. The problem-solving approach to software development described the stages of development from the conception of the need for the software to retirement. The model clearly defines the stage-by-stage progression of the evolution process of

software development. Each stage is an independent part of the process and advancement to the next stage takes place when the requirements of the current stage are completed and well documented. Regression to a preceding stage is allowed by the model, but the software engineer can only regress one level in the model.

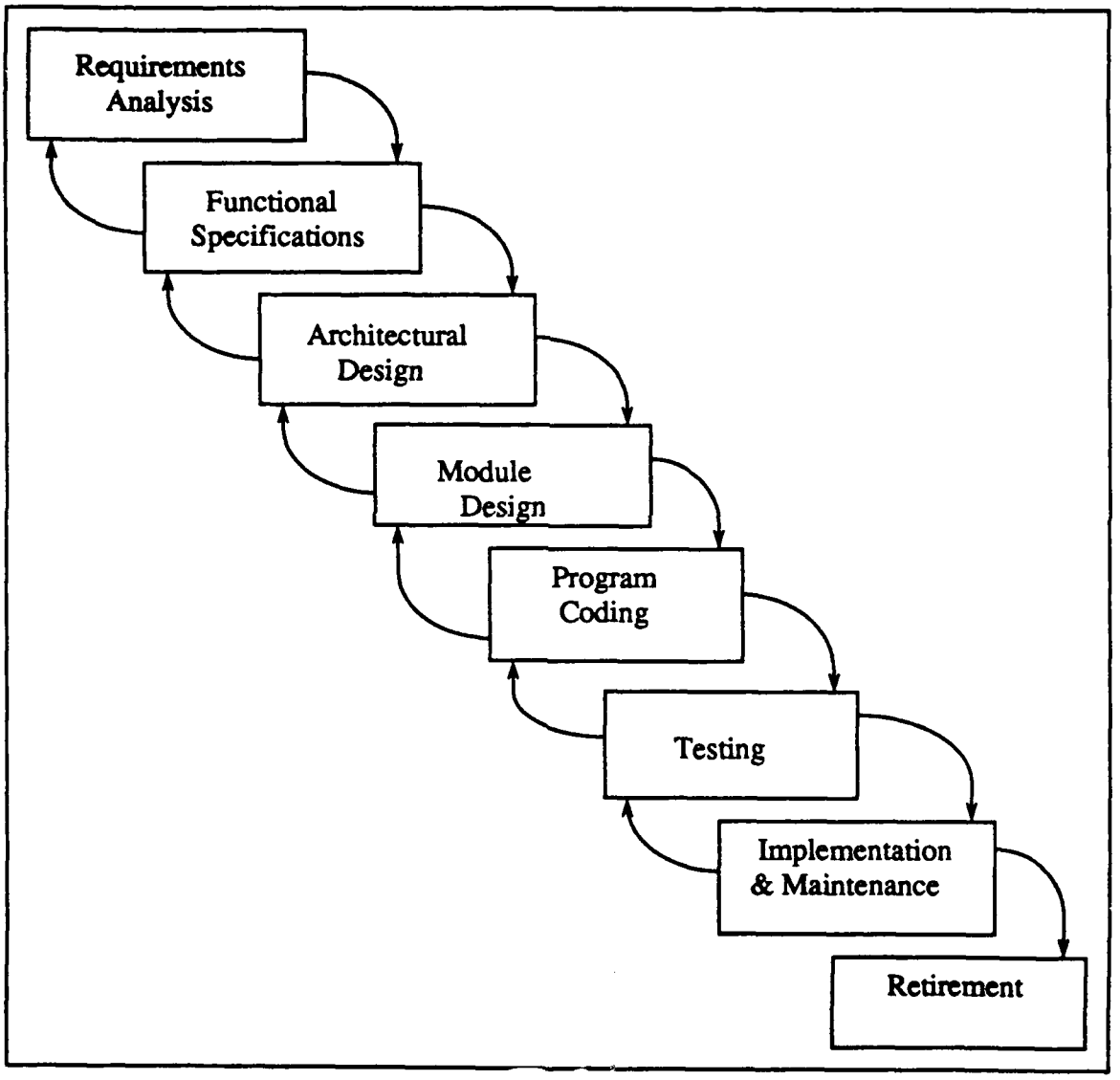


Figure 1. Waterfall Life Cycle Model

The Waterfall Model is primarily designed from the software engineer's perspective. The user is involved with the requirements analysis phase, but then the user merely waits for the software product in the implementation phase. The lack of user interaction in the middle to latter phases of the model usually degrades the requirements engineering process. Clear and concise definition of user requirements are necessary to allow engineers to develop software to meet the user's needs. In addition to clear and concise definitions, the requirements definition must remain static throughout the evolution of the software. This is necessary because of the limitations of regressing to a former stage, particularly after the architectural design phase is completed.

Since its introduction, the Waterfall Model has guided the thinking of both DoD and the civilian software industry. "Most "standard" life cycle models that exist today are based on the Waterfall Model". [Ref. 5: p. 1454] The fact that the Waterfall Model has survived two decades is testimony to its wide acceptance as a sound life cycle model. But the rapid advancements in computer technology and the software engineering community's inability to solve the requirements engineering problems has driven many researchers to look at alternative life cycle models which will reflect current technology capabilities and society's growing software requirements.

a. DoD Acceptance Of The Waterfall Model As Its Standard

DoD suffered through much of the 1970's with software failures and mismanagement of software development projects. The authors revealed in [Ref. 7: p. 1] that results of a Government Accounting Office (GAO) study of randomly selected federal government software development/acquisition projects indicated that, of the dollars spent on projects in the 1970's, 29% resulted in delivery of no software, 47% bought

software that was not usable, 19% bought software that required extensive rework before it could be used (most of which was discarded due to difficulty in maintaining or modifying it), and only 5% bought software that was either usable as delivered or after minor modification.

The mounting requirements for software applications in future weapon systems led DoD to accept the Waterfall Model as the standard for software development and acquisition in the early 1980's. Numerous regulations were published, notably MIL-STD-1679A (Weapon System Software Development, 1983), DoD-STD-2167 and DoD-STD-2167A (Defense System Software Development, 1985 and 1988 respectively), depicting a life cycle that fits the traditional mold of the Waterfall Model. A key point to note in DoD's acceptance of the Waterfall Model as standard policy was the lapse of at least 10 years before it became the standard. The primary reason for this is that the process of instituting or changing policy in DoD is extremely regulated. Another reason for the delay is DoD's reluctance to introduce innovative methods that have not been thoroughly tested and evaluated.

b. Problems With The Waterfall Model By Current Technology Standards

Although the Waterfall Model has been in existence nearly two decades and has become the standard for DoD software development and acquisition during the last decade, serious problems exist that are considered unacceptable by today's standards. The technology is changing so rapidly that often there is incomplete knowledge about software objects, software processes, and available software tools. Often designers and software engineers do not keep current on advances in their field. While the technological advances pose problems for current software development processes, it is not the determinant factor in the community's elevated interest in

introducing alternative software development methodologies. The major problem lies in the software engineering community's frustration and inability to solve the persistent problem of requirements engineering. While there is a resurgence of a need to replace the traditional Waterfall Model, the fact is that the methodical foundation and the scientific approach it brought to the community will forever be the standard from which new models will be devised.

4. Requirements Engineering *(Past/Present)*

Requirements engineering is the process of identifying the user's requirements, systems requirements, and validating the requirements at the time of software implementation. Prior to Royce's Waterfall Model, users were often absent during the entire process. They were usually just a receiver of the software, having to adjust to its inadequacies. Royce was cognizant of the needs of the user and the importance of input from the user on his or her needs and requirements. Unfortunately, the environment that Royce envisioned to implement his software development process was only present in theory, not in reality.

a. Requirements Analysis

Royce envisioned the user's requirements to be clear, concise, and static throughout the evolution process. In reality, the requirements often were vague and constantly changing throughout the evolution of the software development process. An enormous amount of research was devoted to making the identification and communication of requirements clearer. Users claimed that designers could not translate the stated requirements into software production. Designers claimed that users did not know what they wanted and were often changing their requirements. The accusations and extensive research produced voluminous requirements documents that were

confusing to both parties. The common practice was to create the requirements document merely to meet the acquisition requirements. Little of the documentation was actually used in later stages of the development process. The problem still exists.

The problem of users not being able to communicate their requirements is divided into three separate categories: known requirements, unknown requirements, and technological changes. There are some requirements that are known by the users, but the art of communicating them to others and transferring those requirements to paper is a problem that has haunted the software development process from the beginning. There are also unknown requirements that users either don't consider or are not apparent until after the requirements document is completed. Advances in computer technology may be unknown to users and designers at the requirements phase.

The underlying problem is that requirements engineering is rarely a static process. It is dynamic and does not stop after the requirements phase is completed. The Waterfall Model doesn't support the dynamic nature of requirements engineering. If requirements change, the development process must regress to the initial phase and the entire process starts over again. This leads to problems in meeting both production costs and completion time constraints. The result is late deliveries of software and severe cost overruns. This is unacceptable to both designers and users.

b. Requirements Validation

Requirements validation is the process of ensuring that the user's requirements are being implemented as required. In the Waterfall Model, validation is done at the testing phase and upon delivery of the system. The validation that is done at the testing phase is conducted by software engineer testing groups, without the user's feedback. So, the validation of requirements is based solely on the requirements

document which is published in the initial phases of the model. The user finally validates the software after program coding, testing, and implementation. Frequent cost overruns and late deliveries reflect the problems associated with users validating the software so late in the process. Errors or misrepresented requirements may not be recognized until the software is completed. Users are rarely amenable to paying for software that doesn't meet their needs. The software industry cannot continue to survive with unsatisfied customers and a reputation for software cost gouging and late deliveries of software products.

5. Boehm Spiral Model

One of the most notable attempts to refine the Waterfall Model was Boehm's Spiral Model introduced in 1976 [Ref. 7: p. 2]. Boehm explained in [Ref. 4: p. 16] that the Spiral Model starts with a hypothesis that a particular operational mission could be improved by a software effort. The spiral process continually tests the hypothesis. At any time if the hypothesis fails the test (for example, if delays cause a software product to miss its market windows or if a superior commercial product becomes available), the spiral is terminated. Otherwise, it terminates with the installation of new or modified software, and the hypothesis is tested by observing the effect on the operational versions. This model was moderately accepted by the software engineering community, but DoD never instituted it as their standard for software development and acquisition.

B. OBJECTIVES

The objectives of this thesis are to conduct an extensive survey and evaluation of proposed alternative software life cycle methodologies and published software life

cycle models and to determine the most appropriate software life cycle model to support future DoD software needs and implementation of rapid prototyping methodologies.

C. ORGANIZATION

A survey of the rapid prototyping process and the alternative software life cycle methodologies and models will be presented in Chapter II. An analysis and evaluation of the proposed alternative rapid prototyping methodologies will be presented in Chapter III. An analysis and evaluation of the proposed alternative rapid prototyping models will be presented in Chapter IV. Future DoD software engineering requirements are discussed and proposed strategic, near-term, short-term, and long-term goals are presented in Chapter V. The conclusion is presented in Chapter VI.

II. RAPID PROTOTYPING

Growing software demands, advances in computer hardware technology, and continuing frustrations in solving the requirements engineering dilemma have driven the software engineering community to review existing software development methodologies and to pursue alternative life cycle models. Research conducted during the past decade suggests that the most appropriate alternative software development methodology is rapid prototyping. The rapid prototyping paradigm is certainly not seen as the solution to all of the software engineering problems, but offers improvements in numerous areas. "Rapid prototyping is particularly effective for ensuring that the requirements accurately reflect the real needs of the users, increasing reliability, and reducing costly requirements changes". [Ref. 8: p. 25]

One definition of a prototype is "an original type, form, or instance that serves as a model on which later stages are based or judged". [Ref. 9] In regard to software development, a prototype is an executable model or a pilot version of the intended system. "A prototype is usually a partial representation of the intended system, used as an aid in analysis and design rather than as production software. The construction activity leading to such a prototype is called rapid prototyping". [Ref. 10: p. 1]

The use of prototypes in product development is not isolated to the computer science field. Civilian industry disciplines, such as the automotive industry, have used prototypes for years to define design processes and production line operations. The home building industry is similar by analogy to the software development process in a

rapid prototyping environment. Throughout this chapter, comparisons will be made of the two processes.

The progress of implementation of the rapid prototyping paradigm has not been reflective of the word "rapid". One major reason for the delay is the enormous system support environment and a specification-based prototyping language that must be developed, tested, and evaluated. DoD has been very active in the new paradigm through research funding and in sponsoring rapid prototyping conferences and workshops.

The dynamic changes in technology and advances in research have resulted in the publication of alternative strategic representations of the rapid prototyping paradigm. Currently there are at least five rapid prototyping methodologies. Unfortunately, these theoretical methodologies have resulted in few models that provide the degree of specificity or detail to actually implement rapid prototyping in civilian industry and in DoD.

This chapter will provide an in-depth discussion of the rapid prototyping process and the impact of its development. The system support requirements and their effect on the implementation of prototyping will be discussed. The discussion of the requirements engineering process will continue from Chapter 1, concentrating on the present to future states with respect to the introduction of the rapid prototyping paradigm. This chapter will conclude with a presentation of the five most notable and researched rapid prototyping methodologies and three of the published rapid prototyping models.

A. RAPID PROTOTYPING PROCESS

The rapid prototyping process is more complex than the conventional definition suggests. The development of a software prototype, under real-time constraints, differentiates the software industry from other civilian industry prototyping processes. "In the rapid prototyping paradigm, the traditional software cycle used in software design is replaced by an alternative life cycle which consists of two phases, rapid prototyping and automatic code generation". [Ref. 10: p. 2] Current technology precludes automatic code generation, but intermediate processes are available to produce partial code generation. In contrast, technology is currently available to implement rapid prototyping.

The rapid prototyping methodology in a typical feedback loop is presented in Figure 3 [Ref. 10: p. 3]. Rapid prototyping initially establishes an iterative process between the user and the designer to concurrently define specifications and requirements for the time critical aspects of the envisioned system. The designer then constructs a model or prototype of the system through a high-level specification-based prototyping language. Janson describes the process in [Ref. 2: p. 3] where the prototype is a partial representation of the system, including only those critical attributes necessary for meeting users requirements, and is used as an aid in analysis and design rather than as production software. During demonstrations of the prototype, the user validates the prototype's actual performance against the expected performance. If the prototype fails to execute properly or to meet any critical timing constraints the user identifies required modifications and redefines the critical specifications and requirements. This process continues until the user determines that the prototype successfully meets the time critical aspects of the envisioned system.

Following the final validation, the designer uses the validated requirements as a basis for the design and eventual manual coding of the production software.

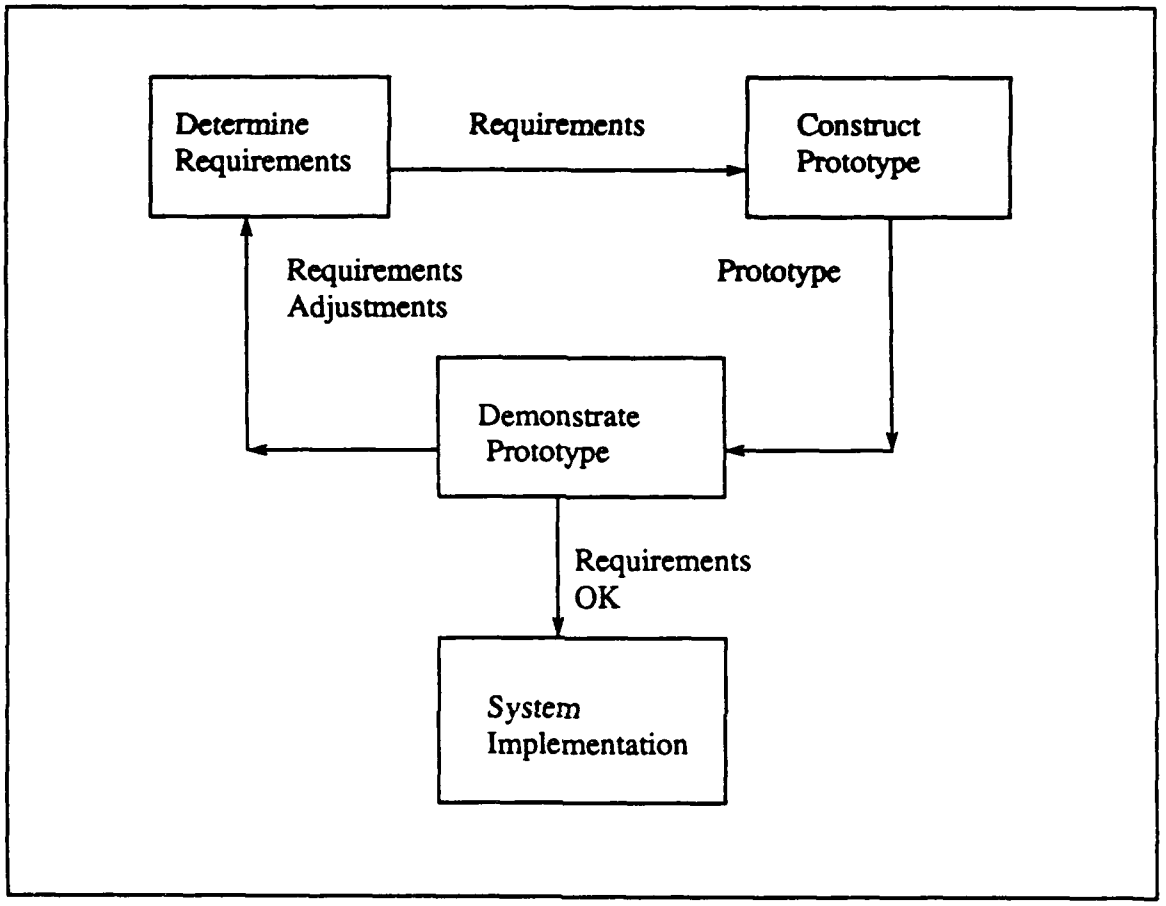


Figure 3. Rapid Prototyping Methodology

The conventional rapid prototyping process described above has some similarities with the home building process, as reflected in Figure 4. Both disciplines are focused on ensuring that users needs and requirements are met within the environmental constraints. "Rapid Prototyping has emerged as a solid technique to improve one aspect of productivity, that of delivering the right system that will evolve as the user's needs change" [Ref. 8] The home builders, in similar fashion, strive to construct a home that will either appeal to or meet prospective owners needs and requirements.

Home Building	Software Development
Environmental Survey/ Prospective Owners Requirements	Requirements Analysis
Architectural "*Blueprint*" Design	Specification Analysis/Design
Develop Small Scale Model	Build Software Prototype
Perspective Owner Approves Model	Prototype Validation
Construct Home	Manual Coding of Production System Software

Figure 4. Comparison of Home Building and Software Development Processes

The conventional rapid prototyping process is seen merely as a skeleton foundation of the proposed paradigm. While the use of prototypes to validate user requirements during the initial stages of software development has been positively received, the manual coding is seen as archaic and needless by many researchers. Computer-Aided Software Engineering (CASE) techniques provide systematic supporting tools that meet the real time needs and put the "*rapid*" in rapid prototyping.

Referring back to the home builders/software developers analogy, the efficient use of all available resources allow the product to be constructed rapidly. Home builders rarely build homes from scratch, but rather put together pre-fabricated portions. Similarly, software developers rarely build software from scratch. They often import code from other software for their specific applications or functions. Recent research efforts point to reusable software components, stored in a software knowledge base, as the intermediate stage to limit manual coding and to ultimately achieve automatic code

generation. Figure 5 displays the additions of pre-fabrications/reusable components in the home builders/software developers analogy.

A computer aided rapid prototyping approach will provide the software designer with a powerful tool, designed specifically for development of hard real-time or embedded systems. Although the traditional approach may also produce an acceptable product, rapid prototyping offers significant advantages in several major areas. Designing a simplified executable prototype of the envisioned system forces the user and designer to decompose a complex system into its major components. This process creates modules that individuals can easily understand and manage. This modularized design is enforced by a formal, prototyping language based on abstractions of the systems requirements and high-level constructs.

Home Building	Software Development
Environmental Survey / Perspective Owners Requirements	Requirements Analysis
Architectural "*Blueprint*" Design	Specifications Analysis/Design
Develop Small Scale Model	Build Software Prototype
Prospective Owner Approves Model	Stakeholder Validates Prototype
Transport Pre-Fab Material to Construction Site	Retrieve Reusable Software Components
Join Pre-Fab Portions	Link Reusable Components
Owner Moves In	System Implementation

Figure 5. Pre-Fabrications/Reusable Components Comparisons

Janson points out in [Ref. 2: p. 5] that a computer-aided rapid prototyping approach using a modularized design focuses the designer's attention on analysis of the

requirements and specification of the system. At this stage, the designer should concern himself with the architectural decomposition of a complex system rather than becoming engrossed with detailed programming efforts inherent in conventional prototyping. This approach allows the user to verify requirements and to identify problem areas early in the development cycle. This verification process eliminates some of the expensive redesign efforts and increases the user's confidence in the system..

B. SUPPORT SYSTEM FOR RAPID PROTOTYPING

The speed at which the rapid prototyping paradigm is instituted may very well be dependent on the development of the necessary support system. "An automated support system environment is essential for the rapid construction of prototypes". [Ref. 10: p. 29] There has been a considerable amount of research on prototyping tools which will comprise the support system environment. One perspective of what the environment should contain is the notion of a prototyping center. A generic list of tools that the prototyping center should include are presented in Figure 6 [Ref. 11].

Researchers agree that a prototyping system must provide tools that fulfill these basic requirements. A *Text Editor* is required to provide word processing functions during the program code generation, documentation, and modification. The *Data Base Manager* is required to manage a reusable software component knowledge base. A *Procedural Language Program Generator* is vital to fulfill the automatic code generation goals of the paradigm and to manage the enormous components library. *Teleprocessing* is vital, especially considering the enormous databases and the increased importance on meeting real-time constraints. Some commercial software feature automatic *Screen Generators*. Screens are becoming standardized

and can be automatically generated from the user's screen specifications. The *Dictionary Maintenance Tools* are necessary to insure the interface between designers, prototyping languages, and the knowledge base. The *Non-Procedural Report Writer* is similar to a data flow generator which will provide the historical development of the software. The *Interactive Query Language* is the communication link between designers and the system (e.g., when retrieving reusable software components). Finally, the *Documentation Generator* is essential considering the poor reputation that programmers have of documenting software and the problems associated with interpreting the computer generated code. Each of these tools have been, and will continue to be, topics for independent research. The intent of covering the generic tools is to provide emphasis of the complexity of the support system.

A Text Editor	*Dictionary Maintenance Tools*
A Data Base Manager	*A Non-Procedural Report Writer*
A Procedural Language Program Generator	*An Interactive Query Language*
A Teleprocessing Monitor	*A Documentation Reporter*
A Screen Generator	

Figure 6. Prototyping Center Tools

Although there has been quite a bit of research on the tools required for the new rapid prototyping paradigm, there has been very little research published on a complete and theoretically sound prototyping system. There have been many subsets, but the most complete published rapid prototyping support system is the *Computer Aided Prototyping System* (CAPS), at the Naval Postgraduate School. CAPS will be

discussed in more detail in section D.1 during the discussion of CAPS Rapid Prototyping Model.

The development of independent support system tools is innovative and complex. It is unlikely that the software engineering industry will implement a complete prototyping system in the near future. Just as software development is a dynamic process, the development of the prototyping tools is also dynamic. Advances in computer hardware technology, particularly in the progress of concurrent and parallel processing, will play a major role in the prototyping tools development process. Improvements in operating systems environments will also be important. There has been some debate over the requirement for a specific prototyping language. These areas will be discussed as future considerations for the implementation of the rapid prototyping paradigm.

1. Prototyping Language

There is not agreement on whether a new prototyping language is necessary to implement the new paradigm. The researchers that reject the need for a prototyping language are primarily in the Management Information Systems (MIS) environment and have small scale applications. One such application is a public accessing kiosk used by Aetna Life and Casualty, which is executed on a MacIntosh Computer System. The authors of [Ref. 12] discard the additional requirements for a prototyping language and state that mere understanding of the system will enable the production of prototypes. They contend that existing relational data base languages are adequate to develop the prototypes for their applications. The specifications are validated by using a storybook technique of displaying the prototypes on a wall in hierarchical fashion. While this approach may be relevant in some cases, the need for a

prototype on such small scale applications is suspect. The rapid prototyping paradigm is intended theoretically for large real-time systems, which fit the majority of DoD's current and future software needs.

"The languages used in the CASE paradigms differ from the languages used in traditional software development because of the need for supporting a higher level of automation at the early stages". [Ref. 13: p. 1] The only existing programming language that has the potential to support rapid prototyping is DoD's programming language Ada. Though Ada lacks adequate semantic qualities and specification-based requirements some researchers, such as Dr. Winston Royce, feel that modifications to the existing language would provide the language requirements necessary to support the rapid prototyping paradigm. If Ada is modified, two serious concerns are raised. The first and most important is DoD's willingness to support the proposed modifications and handle the additional problems associated with maintaining and retrofitting existing DoD software. The second is whether, after the modifications are made, there will be any resemblance to the present Ada language. This concern supports the need for a new prototyping language. However this is resolved, the language that will support the new paradigm must be formal and must contain both specification and design based features.

Dr. Berzins explains in [Ref. 13: pp. 2-3] that a *formal* language is a notation with a clearly defined syntax and semantics. Formal languages are critical components of a CASE environment because they are needed to achieve significant levels of computer-aided design with currently feasible technologies. Automated tools are capable of detecting structure in a notation only if the structure has been formally defined, and of responding to aspects of its meaning only if the meaning of the aspect

has been formally defined. The tools applicable to informal notations usually treat them as uninterrupted text strings, which limits the tools to bookkeeping functions, such as version control. Notations with a formally defined syntax, but informal semantics can support tools sensitive to the structure of the syntax, such as pretty printers and syntax-directed editors. If both the syntax and semantics of a special purpose language have been fixed and are clearly defined, it becomes possible to create automated tools for analysis, transformations, or execution of the aspects of the software system captured by the language and its conceptual model.

Dr. Berzins points out in [Ref. 13: p. 5] that formal specification languages are the basis of CASE. An adequate specification language will have the maximum expressive capability and formalism for supporting mechanical processing of software. To fully support the CASE requirements, integration of the specification language, design language, and prototyping language are necessary. The main purpose of a specification language is to define the interface or to record a specification. A specification is a black-box description of the behavior of a software system or one of its components. A black-box description explains the behavior of a software component in terms of the data that crosses the boundary of the box, without mentioning the mechanism inside the box. The design language defines the structure of the system. A design is a glass-box description of a software system or component. A glass-box description gives the decomposition of a component into lower-level components and defines their interconnections in terms of both data and control. A specification says what is to be done and a design says how to do it.

Prototyping languages are designed to produce executable prototype versions of the production system, to be able to demonstrate the real-time constraints, and to

record and test interfaces and interconnections. The prototyping language defines the executable model of a system by using both black-box and glass-box descriptions. A prototyping language has no obligation to define detailed algorithms for all components of the system as long as it is descriptive and produces an executable prototype. It supports simple and abstract system descriptions, locality of information, reuse, and adaptability at the expense of execution efficiency. Dr. Luqi presented a survey in [Ref. 14] of two specification-based languages, MSG (MeSsaGe) and SPEC (SPECification Language); and a specification/design-based language, PSDL (Prototyping System Description Language).

MSG is a specification language which is useful for functional specifications. MSG is based on the actor model of computation, where actors are independent active elements that interact solely by sending each other messages. The MSG specification is defined through an algorithm which uses the actor modules and primitive constructs. Experience has shown that MSG is a relatively simple language that is learnable by both experienced and novice programmers. MSG is a formal tool allowing system designers to abstract specifications and to communicate design decisions to each other without getting bogged down in implementation details.

SPEC is a language for writing black-box specifications defined in the functional specification and architectural design of the software system. It is designed to simplify the design and description of large systems without introducing details of the external structure. It assists the analyst in constructing a simple conceptual model for the intended system and to establish and maintain its conceptual integrity. Based on the event model of computation, SPEC uses predicate logic to define the basic behavior of the modules, defined concepts, and an inheritance mechanism that is needed mostly

for specifying large systems. SPEC has precise semantics and a simple underlying model and has been found to sufficiently support mechanical processing.

MSG was the foundational specification language from which SPEC evolved. The major improvements with SPEC are the ability to integrate time into the underlying model, the development of an inheritance mechanism, and the improved locality of information.

PSDL is a combination of specification and design based languages designed to support rapid prototyping. It supports the specification of the requirements for the system and functional descriptions for the component modules. It is designed to handle hard real-time constraints and is based on a simple computation model that closely resembles the designer's view of real-time systems.

Currently compilers and hardware technology do not allow distinctions between different types of languages discussed above. As programming languages become more advanced and hardware technology improves, the probability of complete interaction between hardware and software systems will increase. This advancement will produce a more efficient implementation of the rapid prototyping paradigm. A prototyping language appears necessary. DoD's interest and investment in Ada point to the need to build the prototyping language to interact with Ada or be built upon it.

The issue of whether one prototyping language will be sufficient to meet all the rapid prototyping needs of the future is currently not resolved. Historically we have found that one language does not meet all software development needs. The effectiveness of the prototyping language will be its ability to interact with the tools of the prototyping environment. Since there currently exists only one published

prototyping environment, CAPS, it is difficult to determine if the prototyping language of CAPS, PSDL, is capable of handling all applications of future software development. PSDL appears to be sufficient to handle the underlying requirements of CAPS, and therefore appears to be a good candidate for an acceptable language from which the new rapid prototyping paradigm can be implemented. Since PSDL is currently being written primarily in Ada, it is acceptable to DoD. This is based purely on theory and further evaluation will have to be conducted once the tools and CAPS is fully developed to determine if it truly meets the needs of DoD.

2. Operating System Considerations

There has been a lot of research on how to conduct rapid prototyping. The primitive prototyping tools currently being introduced by industry have raised new concerns in the computer science community. One issue that is rarely discussed in the research of rapid prototyping is how operating systems will support the new CASE tools, reusable software components knowledge bases, and portability. There are two main reasons why this issue is not included in current research papers being published. The most significant reason is that UNIX operating systems and Sun Workstations are currently used for the design and construction of the prototyping tools in academic environments. The other reason is that until hardware architecture is capable of parallel processing, there doesn't appear to be any significant change to the current design of operating systems. Therefore, the current environment is believed to be stable enough to get prototyping into the field and more importantly on the market.

It is clear by the term "*rapid*" that the intent of the methodology is to "rapidly" construct an executable prototype from which requirements validation can be achieved. Theoretically, this should greatly reduce the current problems associated

with requirements engineering. But what are the costs associated with this methodology? This question can be answered by looking at the system environment that affects real-time constraints. The prototyping tools will affect real-time systems. Another element of the methodology is to reduce the amount of human coding by implementing automatic code generation through reusable software components.

Another area to consider is how the operating system will manage the resources necessary to support rapid prototyping. With regard to real-time constraints, one could conclude that multiple processors are required. Single processor systems do not optimize the development process and prevent the process from meeting its true real-time constraints. Concurrent and parallel processing thus become desirable. Rapid prototyping on these powerful operating systems is highly desirable. However, many research problems have to be addressed before it becomes practical. "As hardware architecture advances to support parallel processing, it is believed that modifications can be made to existing prototyping environments to allow processes to run in parallel". [Ref. 11: p. 8] The major impact that parallel processing would have on rapid prototyping is the improvement in prototype production time, moving closer to meeting true real-time constraints.

Bell Labs' UNIX operating system has gained popularity industry wide, as well as in DoD, as the best operating system to support rapid prototyping. One important aspect of UNIX is that it supports concurrency and encourages a tool oriented building block approach to program design. Its resource management, in terms of memory management and input/output mechanisms, is more than adequate for the requirements of prototyping. Paging is an efficient means of managing memory in support of not only the prototyping tools, but also in anticipation of linking reusable software

components from knowledge bases. Currently, UNIX supports fixed-sized paging and uses a first-fit placement strategy. Even though fixed-sized paging and first-fit strategies are subject to memory waste, the benefits outweigh the added costs of increased overhead associated with managing variable-sized paging and best-fit placement strategies. In addition to the stable environment that UNIX's fixed-sized paging offers, the sufficient number of system calls to increase memory for large processes offsets the disadvantages of having fixed-sized pages.

The UNIX-based Sun Workstation is another reason why UNIX is the industry's apparent choice for rapid prototyping. The Sun Workstation is an integrated system which has access to all the library functions and applications pointed out as advantageous in the UNIX operating system. The Sun Workstation provides each process with its own private protected virtual address space. It has internal processors that operate within the UNIX operating system. It offers multi-user and multi-tasking which facilitates designer needs in constructing prototypes.

One popular aspect of the Sun Workstation is the attractive user interface capabilities. The multiple windows, icons, and other sundry interface facets likens the environment to the MacIntosh environment without the PC limitations. This is important because users are generally not computer scientists and therefore are considered novices who have shown great acceptance to the user interface applications.

So, current operating systems technology appears to be suitable for supporting many of the prototyping tools being built. CAPS is currently being built using Sun Workstations. Although these CAPS tools are being built on a smaller scale than theoretically proposed, it appears that the UNIX operating system is capable of supporting them individually. The issue is not whether the independent prototyping tools

can be built on current existing systems, but how the operating system will handle allocating the resources required once the tools are integrated.

To highlight the problem, consider how Ada constructs are used to link packages to build programs. The programmer declares what packages are to be retrieved and linked to other declared packages. The Ada compilation process is criticized by many as too slow in comparison to other programming languages. Now consider the added requirements to constructing the program by using CAPS. However, since the tools perform tasks that must be done manually using other languages, a fair comparison must include manual processes.

The designer declares the specification of the component to be retrieved from the knowledge base. The specifications are then put through the syntax-directed editor to ensure that specifications are syntactically correct. At this time there are portions of PSDL, the reusable software components, and the syntax-directed editor that are residing in real memory. As the components are retrieved and placed in real memory, the graphics editor must also be in real memory allowing the data flow diagrams to be developed or modified. So now there are at least four major prototyping tools in real memory, all executing concurrently. An additional strain is the input/output mechanisms that are being tasked by each of these processes and the use of costly resources. It is clear that the operating system has a much greater task of managing resources with CASE tools.

UNIX has been supporting versions of Ada with relative success, but it is no secret that end users are less than satisfied with the excessive time required for program compilation. This is an important aspect as Ada constructs offer many of the basic fundamental operations that rapid prototyping requires. The generic template,

instantiation in Ada can be used for retrieval of and linking reusable software components from a knowledge base.

The database management strategies and the tools designed to retrieve and link reusable software components play an important part in meeting real-time constraints, but how the system manages memory and input/output operations also affects the speed by which the prototype can be built. There is speculation that the current technology will be able to support reusable software components, but the reality is that the software methodology has not yet been implemented. Although the software engineering community might be initially satisfied, for the sake of getting an initial version, if the implementation suffers some of the same problems that Ada language suffers, the industry will fall short of meeting its rapid prototyping goals.

Although there is no analytical evidence to support whether current operating systems can support the implementation of reusable components, there are concerns about whether creating excessive strains on the system may result in slower systems and possibly force a reevaluation of current technology. The primary reason for the absence of discussion concerning operating systems in researching reusable software components is due in part to the relative success of Ada and UNIX, as well as to the intense research into database management and design to support the implementation. The paradigm calls for the tools to operate with the concurrency associated with the input/output operations of retrieving and linking reusable software components. Current small scale productions, which are being used as prototype versions of the production prototyping system, are functioning efficiently but independent of any other tools or knowledge bases. As the tools are integrated, the system's efficiency and speed of production likely will be an important issue. The question that

needs answering is how much decreased efficiency is acceptable not only today, but in the future.

Since the industry is using operating systems in addition to UNIX, the issue of tools being designed and built on different operating systems strikes at the core of real-time constraints. The performance of a tool on a non-UNIX based system may be very different, faster or slower, than the performance of a tool on a UNIX based systems. This is assuming that the prototyping tools can run on other operating systems. There is a lack of research on this issue. This is mainly due to the economic push to get prototyping into the market with current technology. Another important reason is that tools have not been developed to the point that they are ready to be integrated with other tools, let alone with other operating systems.

The UNIX operating system has continually been upgraded and newer versions unveil more efficient means of managing resources and supporting hardware architectures. It is predicted, by many leading researchers, that production level prototypes are at least a decade away. Current tools take one to two and a half years to build. How many versions of the UNIX operating system will evolve during either of these development periods is unknown. It is certainly an issue worthy of further research to ensure that we don't find ourselves "recreating the wheel" ten years down the road.

The current technology of operating systems, especially with UNIX based systems, is theoretically adequate to support the rapid prototyping paradigm. It is definitely adequate to support the near-term goal which is to build the independent prototyping tools to support the new environment. It is unclear whether the short-term goal of integrating the tools on a small scale prototyping environment can be supported with the current system. In all probability, the environment will be

adequate, even if industry must modify the goals of the paradigm. This modification is driven by the economic incentives for industry to produce a working prototyping system environment. The long-term goal of having executable rapid prototyping environments supporting reusable software components, automatic specifications, design, and coding is many years away.

"As processor architectures have nearly reached their limit in so far as cycle times are limited by the speed of light, the next area of improvement in Computer Science will come from parallel processing". [Ref. 15: p. 50] It may be the case that parallel architecture arrives first. As soon as a parallel architecture is available, operating systems will have to undergo revision. Since this is a very real possibility, the portability and maintenance of our existing or developing prototyping system will have to be modified, at least, and very possible reworked. Even though industry welcomes the dynamic situation, DoD should take a firm stance now on the commitment to rapid prototyping.

3. Software Maintenance

"Software maintenance is a very broad area that includes error corrections, enhancements of capabilities, deletion of obsolete capabilities, optimization, and adaptation of changes in operating environments". [Ref. 16: p. 1128] With software maintenance accounting for well over half of the current software costs, any new software development methodology must account for an efficient software maintenance methodology. The current methodology of software maintenance is presented in Figure 7.

The authors explain in [Ref. 16: p. 1128] that the first phase of the maintenance process consists of program analysis. The second phase consists of generating a particular modification proposal to accomplish the implementation of the maintenance

objectives. The third phase consists of accounting for both logical and performance ripple effects as a consequence of program modifications. The fourth phase consists of testing the modified program to ensure that the modified program has at least the same reliability as before.

The modifications of phase 3 are generally considered the most expensive of the software maintenance costs. The modifications are responses to requirements changes. These enhancements may be planned or unplanned. "It is the unplanned enhancements that are the most expensive because they tend to affect larger parts of the system than with planned changes". [Ref. 17: pp. 2-3]

Dr. Luqi claims in [Ref. 17: pp. 3-4] that the new rapid prototyping paradigm can help to reduce the growing software maintenance costs. The improvements in the requirements engineering process, particularly in the requirements analysis phase, should reduce the costly unplanned enhancements. Prototyping can help reduce maintenance costs by making the original requirements conform closely to the real needs of the users. Systems that correctly implement an accurate set of requirements have lower maintenance costs because there are fewer surprises when the system is put into actual use. Rapid prototyping also helps reduce corrective maintenance by ensuring the system design is capable of meeting the systems performance before substantial effort is spent on system implementation.

The CASE prototyping tools that are vital elements of the new rapid prototyping environments should help to decrease the costs. The tools can increase the leverage of the prototyping strategy by reducing the effort that must be spent by the designer in producing and adapting a prototype to the perceived user needs. The automation of the prototyping process enhances the interaction between the users and designers,

and in resolving unplanned enhancements early in the prototype process rather than after the production system is completed.

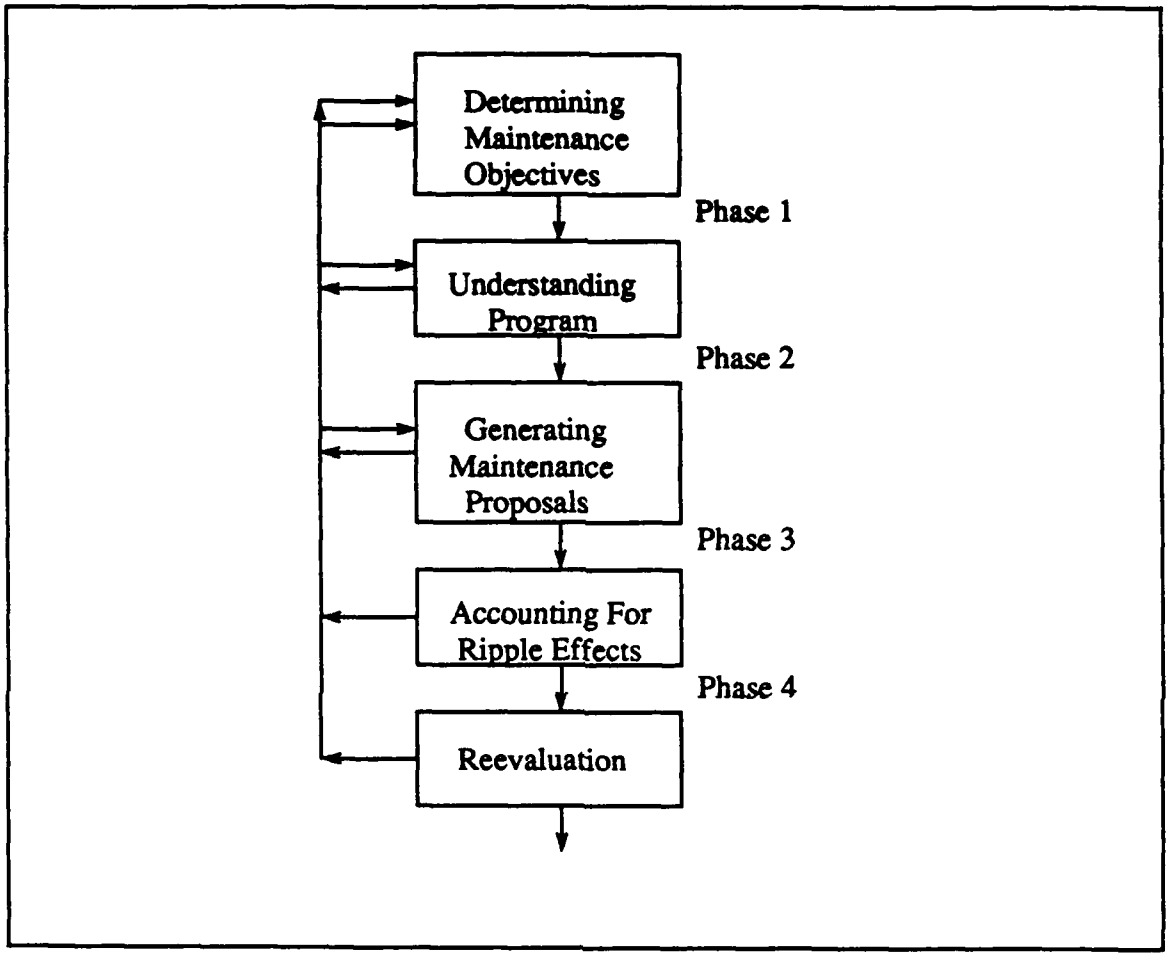


Figure 7. Software Maintenance Methodology

C. REQUIREMENTS ENGINEERING *(Present/Future)*

Requirements engineering has received much attention in the 1980's and undoubtedly will continue to be a target for research in the 1990's and beyond. Requirements engineering in the rapid prototyping paradigm enhances the requirements engineering process of the traditional life cycle model. The need for users to communicate their

requirements to designers and for requirements documentation still exists. The major improvements will be how the requirements are implemented into the software, how the requirements are validated and tested, and how the rapid prototyping model handles changing requirements and enhancements.

1. Requirements Analysis

As noted in 1.4.A, requirements analysis in the traditional model is mired in problems that have been very difficult to solve. "Prototyping is most applicable as a software development approach when *understanding the problem is a problem* - that is in domains where problems are ill structured and poorly understood". [Ref. 18: pp. 211-212] It is not likely that an optimal requirements analysis process will ever be achieved, primarily due to the dynamic state of software demands and computer technology. But significant improvements can be achieved in the near future which will make software production more efficient and amenable to user's needs.

New methods of conducting the requirements analysis process are being evaluated and the communication problems between users and designers have decreased. The new methods demand more group interaction between users and designers. The use of group discussion leaders, usually consisting of junior level/middle-level management from the software industry, has proven successful in defining the user's requirements and ensuring that the designers understand the needs of the users. *Software Storming* is one of the new methods that is presently being implemented at the Mitre Corporation [Ref. 19].

Software Storming is based on the brainstorming problem-solving technique. The process incorporates experts into the initial design and implementation phases of a system, thus combining knowledge engineering with the latest advances in

software development technology and workstation hardware. "Recent evaluations of the software storming process have produced a more functional prototype in four months than the conventional methods do in two years". [Ref. 19: p. 39] The software storming process is presented in Figure 8 [Ref. 19: p. 40]. The difference between the software storming process and the conventional prototyping process is the speed at which the storm process can be completed. The storming process results in an initial prototype and the follow-on phase takes the initial prototype and makes it executable.

The Mitre Corporation used the storming process on a U.S. Army sponsored communication system software project [Ref. 19]. The software product was delivered in a greatly reduced amount of time and at a fraction of the cost of developing comparable software under the conventional means. The results are encouraging, but also subject to speculation. This experiment reveals that if the development time and cost can be reduced without the aid of CASE prototyping tools, then the proposed rapid prototyping paradigm should reduce development time even more. The scope of the project is subject to speculation. The project involved networking in a mobile subscriber equipment system. It was a relatively large system, but was supported by abundant technical specifications and was similar in context to the basic networking theory of Computer Science. For this reason, the ability to meet the determined time constraints of the storming phase is subject to speculation. The other issue is whether the industry and users can devote the dedicated time required by the storming process and how this devotion will affect software production costs in the future.

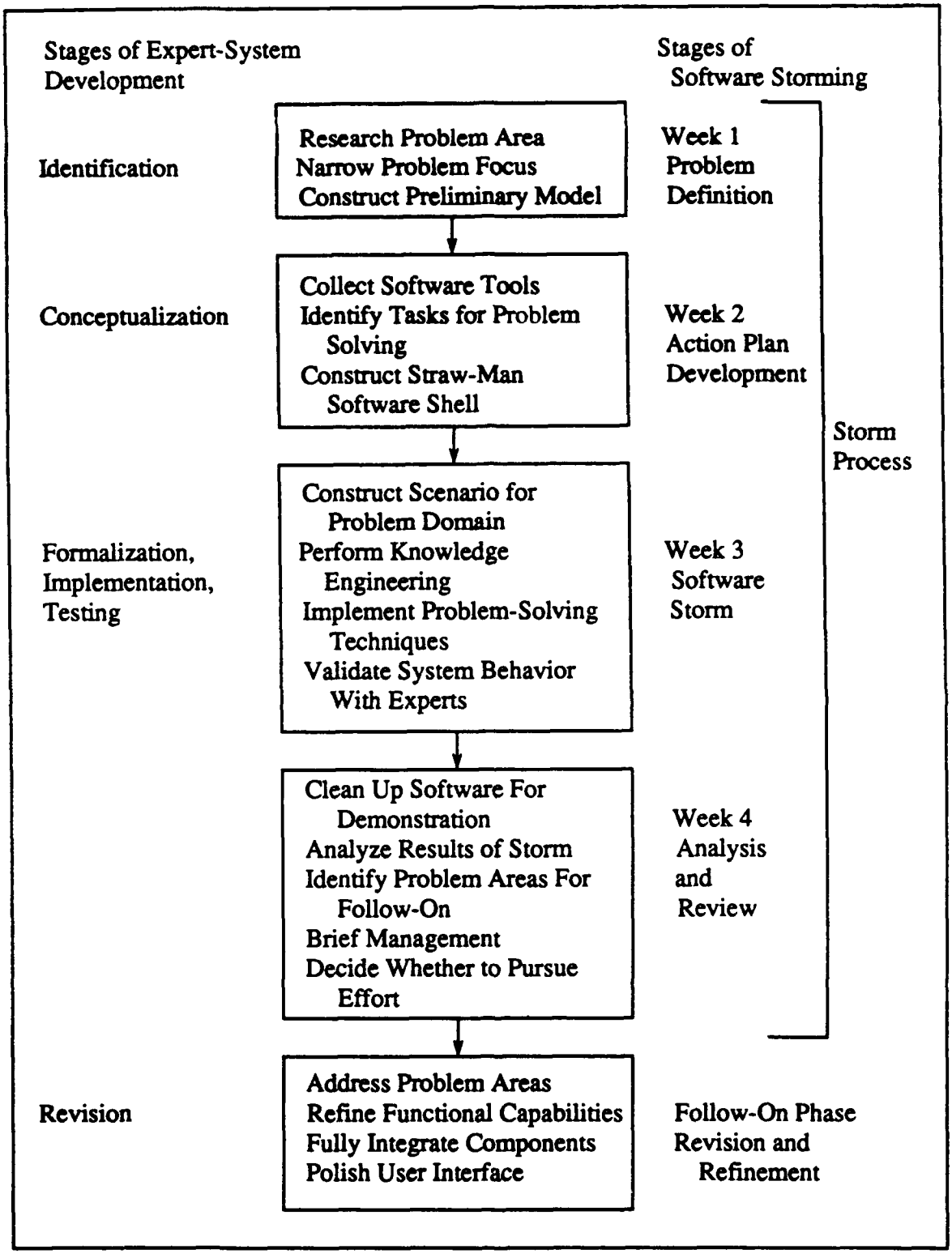


Figure 8. Software Storming Process vs. Expert System Development

It is apparent that through the successful experimentation of new methods, such as the storming process, requirements analysis stages in the future will be oriented on group dynamics and some form of brainstorming techniques. This is definitely a positive move and can be supported by the sociological experiments of the 1970's and early 1980's with group dynamics. The ability to define requirements in the requirements analysis stage will be greatly enhanced by the process of group (users and designers) discussion forums and with executable prototypes.

2. Requirements Validation

The greatest impact that the rapid prototyping paradigm will have on the requirements engineering process is improvements in requirements validation. As discussed in 1.4.B, the conventional life cycle model allowed the initial requirements validation to proceed without the designers in the testing phase, and with the participation of the users only after the software product is complete and delivered. Results of surveys and experience from the 1980's have shown that requirements validation so late in the software development process is costly. Rapid prototyping moves the majority of the requirements validation process up into the requirements analysis phase. This has three major objectives. One is that the users are given the responsibility of validating the executable prototype to ensure that their needs are reflected in the initial versions of the software. The second objective is to reduce production costs. By validating the prototypes so early in the process, the costs associated with making modifications or enhancements are reduced because the prototype is on a smaller scale than the larger production system. The ripple effects are reduced and therefore maintenance costs are greatly reduced. The last major objective is that before the software goes into the production phase, requirements validation is for the most part

complete, and the validation increases the probability of user satisfaction upon delivery. Although requirements validation continues throughout the software development process, with validation of the software upon delivery, discrepancies in stated and executed requirements should be minimal. This enhancement to the requirements engineering process will improve the traditional process, but will not provide the optimal solution. The problem of dynamic requirements changes, particularly during the system implementation phase, will have to be addressed. The task of regressing to the requirements phase in the rapid prototyping paradigm is much easier and less costly than to do the same in the traditional model. Although the mechanics of regressing back to early stages is improved, the problem of meeting delivery deadlines becomes a concern. While the optimal solution may not be currently available in research publications, the tremendous improvements made in the rapid prototyping paradigm certainly rejuvenates the computer community's hope for achieving that goal.

D. ALTERNATIVE SOFTWARE ENGINEERING LIFE CYCLE METHODOLOGIES AND MODELS

The current problems associated with the traditional Waterfall Life Cycle Model have resulted in the need for an alternative software engineering life cycle model. The problems of the traditional model have been presented in Chapter 1. The new rapid prototyping paradigm has been represented in generic terms in the previous sections of this chapter. There are, however, differing perceptions on how to implement the new paradigm. There are five different methodologies for implementing the new paradigm. These methodologies cover the spectrum of the ability to implement the

paradigm in the near-term, short-term, and long-term with regard to computer technologies.

Each of these methodologies are supported by valid scientific and problem-solving means. Unfortunately, the extensive research and publication of these methodologies has resulted in only three published rapid prototyping life cycle models. There may be more models being developed, but they are either only locally published in academic institutions or have not been completed. Undoubtedly we will see more models, especially as the current published models near implementation and undergo evaluation.

1. Alternative Methodologies

"A methodology is the system of principles, practices, and procedures applied to any specific branch of knowledge". [Ref. 8] With respect to software development, these methodologies are the global or strategic principles of how the proposed paradigms should be modeled for implementation. The architects of these alternative methodologies do not refer to them as life cycle models. They evolve into life cycle models, as did Dr. Royce's Waterfall Model. Any one of these five methodologies may become the software life cycle model of the 1990's or in the next century. The most probable is that an integration of two or more will eventually be the standard for software development of the future.

a. Rapid Throwaway Prototyping Methodology

The authors noted in [Ref. 7: p. 5] that the rapid throwaway methodology addresses the issue of how to ensure that the software product being developed will meet the user's needs. An informal representation of the rapid throwaway prototyping methodology is presented in Figure 9. The rapid throwaway prototyping approach is to construct a "quick and dirty" partial implementation of the system prior to

(or during) the requirements stage. The potential users utilize this prototype for a period of time and supply feedback to the developers concerning its strengths and weaknesses. The feedback is then used to modify the software requirements specification to reflect the real user's needs. At this point, the software developers can proceed with the actual system's design and implementation with the confidence that they are building the "right" system (except in those cases where the user's needs evolve). An extension of this methodology uses a series of throwaway prototypes culminating in full scale development.

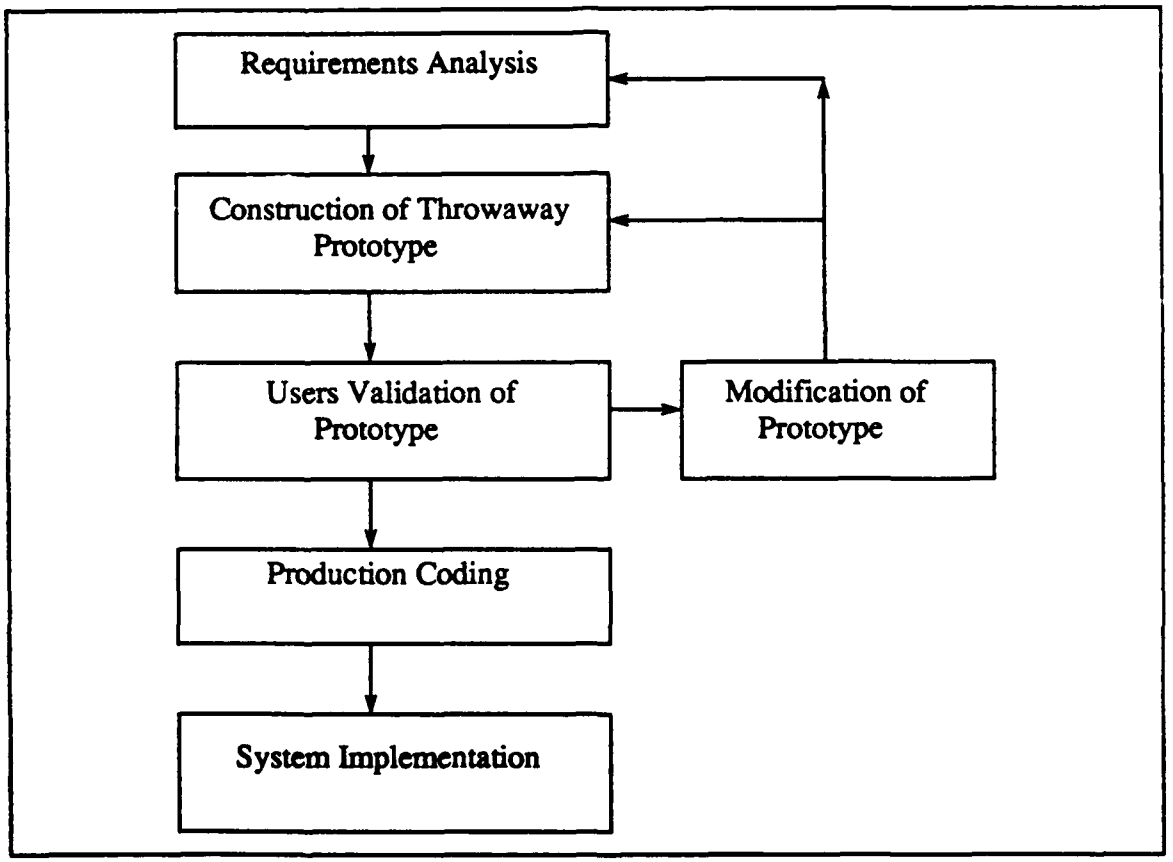


Figure 9. Rapid Throwaway Methodology

The objective for rapid throwaway prototyping is to improve the requirements engineering process. This methodology does not specifically address the procedures

following the requirements phase, but it is implied that it would follow the same general stages as the traditional model. The functionality of the prototype is merely to define the requirements and design features to meet the user's needs. The prototype will not be used as actual coded software in the production system. The implementation of this methodology can be seen as a near-term goal, given the development and implementation of the prototyping tools that allow the rapid development of the throwaway prototypes.

b. Incremental Development Methodology

The authors explain in [Ref. 7: p. 6] that the incremental development methodology is a process of constructing a partial implementation of a system and incrementally adding functionality or performance enhancements. This methodology reduces the costs incurred before an initial capability is achieved, provides a means of evaluating the functionality developed earlier, and allows the blending of evolving user's needs with future planned increments of the system . An informal representation of the incremental development methodology is presented in Figure 10.

When an incremental development methodology is used, the software is deliberately built to satisfy only a subset of the total requirements. However, it is constructed in such a way as to facilitate the incorporation of both remaining and new requirements, therefore providing a more adaptable system. The target objective for this methodology is also the requirements engineering process. By developing the prototypes incrementally, the requirements and design of the software are refined and the incremental prototypes are validated by the users at each progressive stage in the development. The increments are relatively small, replicating a step-wise refinement process. Just as in the rapid throwaway methodology, the prototype is not used

in the actual production system, but is used merely to explicitly define the requirements and design. The incremental development methodology attempts to produce incremental prototypes of every possible requirement or set of requirements. It is much more effort intensive than the rapid throwaway methodology, but the explicit definition of requirements and design features facilitate ease of coding during the system implementation phase.

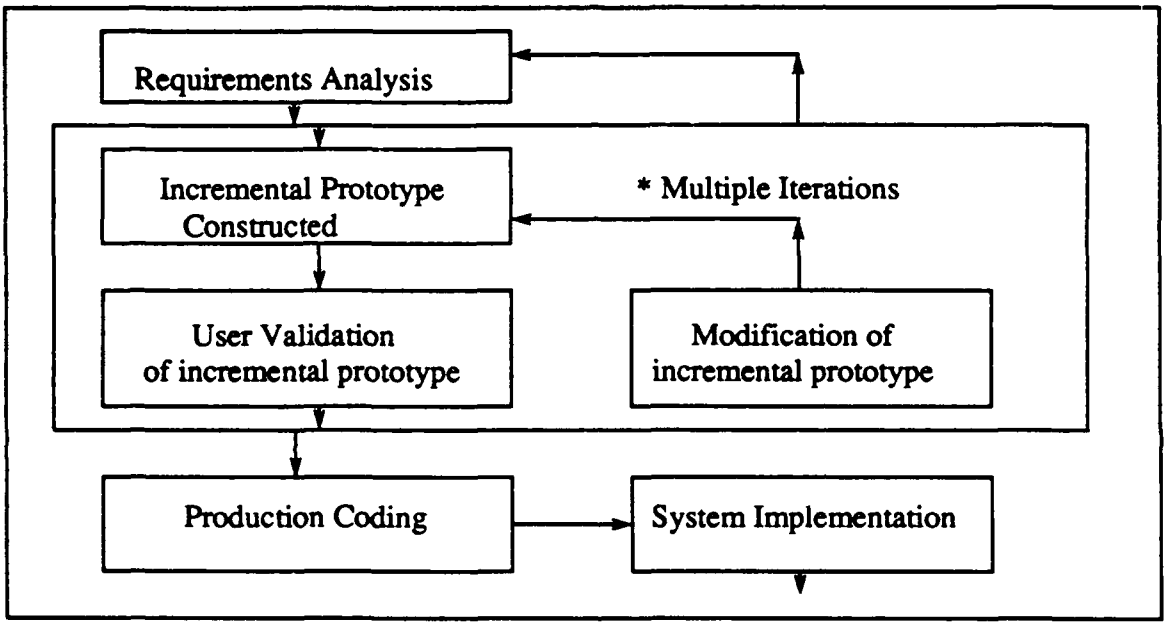


Figure 10. Incremental Development Methodology

c. Evolutionary Prototyping Methodology

The authors noted in [Ref. 7: p.7] that the evolutionary prototyping methodology is a combination of the rapid throwaway prototype (except we keep the prototype) and incremental development. An informal representation of the evolutionary prototyping methodology is represented in Figure 11. This methodology has been viewed as a way to eliminate the formal written requirements specifications. In evolutionary prototyping, the initial efforts focus on the development of an evolvable architecture,

as well as a part of the system functionality which meets a known set of requirements. The executable prototypes are then used operationally by the users in order to understand the remaining requirements better. Evolutionary prototyping differs from incremental development in that we do not initially understand all the requirements and need to experiment in an operational environment to learn them. With incremental development we understand the requirements but implement them in subsets of increasing capability. Also, evolutionary prototypes tend to focus on the best understood points of the system and build upon strengths, whereas throwaway prototypes focus on those aspects that are least understood. The development of evolutionary prototypes (which evolve into operational systems), is not necessarily "rapid", since reliability, adaptability, modularity, and performance are required in an operational system, and are major time consuming development features.

The evolutionary prototyping methodology is more efficient than the two former methodologies since it uses the prototypes as part of the production system and re-coding does not have to be done. This reduces the possibility of program coding errors or design differences from the actual prototype the user validated. The methodology should result in a production system that more closely meets the user's requirements and needs and should be less costly in terms of production. The process of developing an evolutionary prototype is very complex and tool dependent. The implementation of this methodology is more of a short-term goal of the computer industry, with the actual development of the prototyping system symbolizing the fuel that propels its implementation.

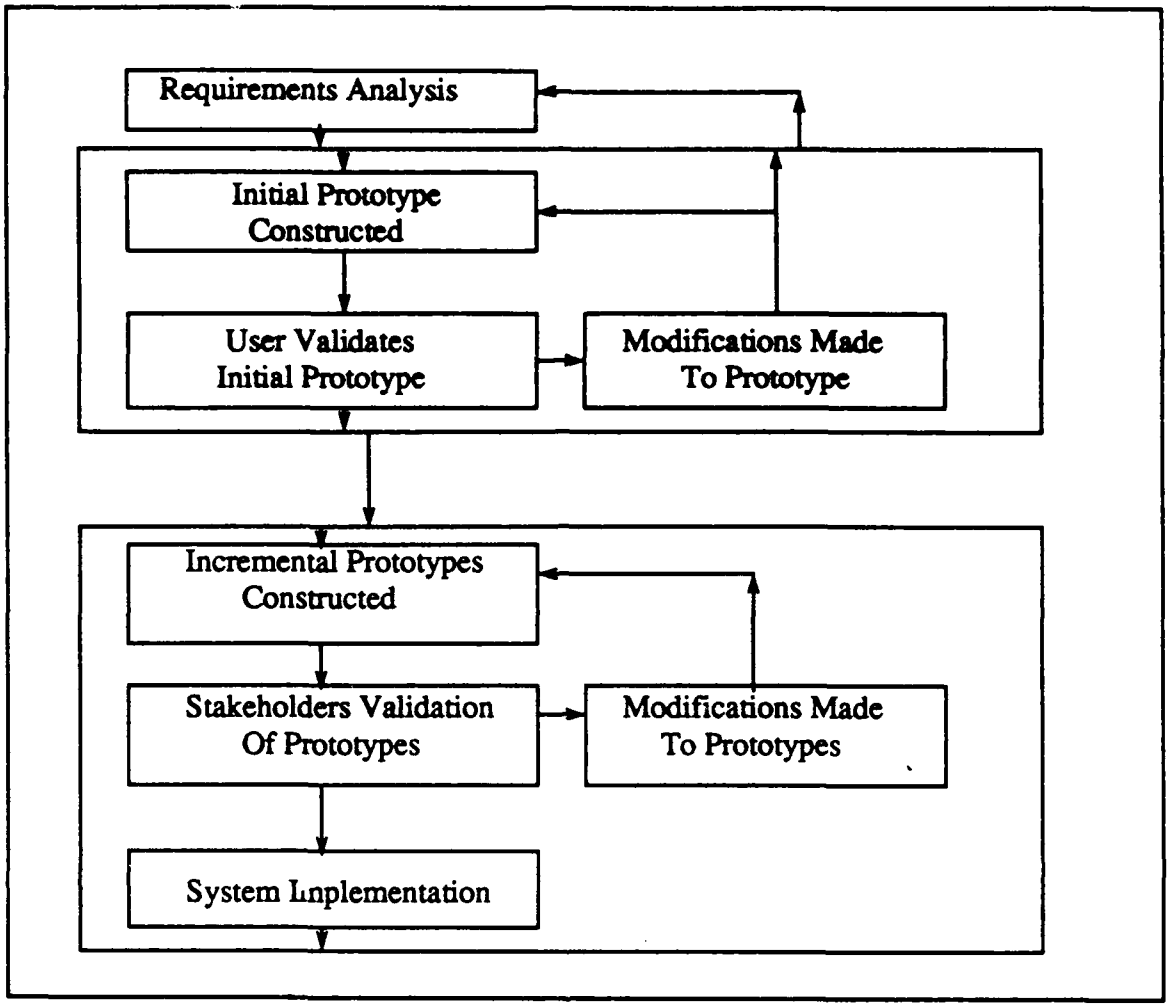


Figure 11. Evolutionary Prototyping Methodology

d. Reusable Software Component Methodology

The authors mention in [Ref. 7: p.7] that few programmers construct software programs entirely from scratch. They use portions of existing software to perform particular functions or applications rather than rewriting code over and over again. Even so, the software industry has been properly accused of continuously reinventing the wheel. A reusable software methodology will reduce development costs and increase reliability by incorporating previously developed and proven designs and code into new software products. An informal representation of the reusable software

methodology is presented in Figure 12. The benefits of reusing components would be shorter development schedules (less new design, code development, and less first time testing) and more reliable software (by using components that have been previously "shaken down".

The reusable software methodology is theoretically sound and extremely important to the successful implementation of the rapid prototyping paradigm. However, there is a cost associated with developing this methodology. The reusable software components must be written in a common language that allows adequate interface when components are linked. The issue of what language to write the components in has been discussed in some publications, but it appears that since DoD is a major proponent in the software development industry, Ada is the most logical choice. As discussed earlier, a specification-based prototyping language is required to enable definition of specifications and retrieval of the reusable components from the software base. The development of the knowledge base is a complex task and the interface between it and the prototyping language is critical. Because each depend on the other, there appears to be a deadlock in their independent development. Another issue is memory availability and how to store and manage the monstrous software component library necessary to support the rapid prototyping paradigm. Through research efforts in the artificial intelligence field, expert systems will inevitably contribute to the successful implementation of reusable software components.

e. Automated Software Synthesis Methodology

The authors explain in [Ref. 7: pp. 7-8] that automated software synthesis is a methodology whereby requirements or high-level design specifications are transformed into operational code. An informal representation of the automatic software

synthesis methodology is represented in Figure 13. The transformation process may be directed by algorithmic or knowledge-based techniques. Each generation of software engineering researchers applies the term software synthesis to one language "higher" than the one currently used in programming. Thus, when machine language

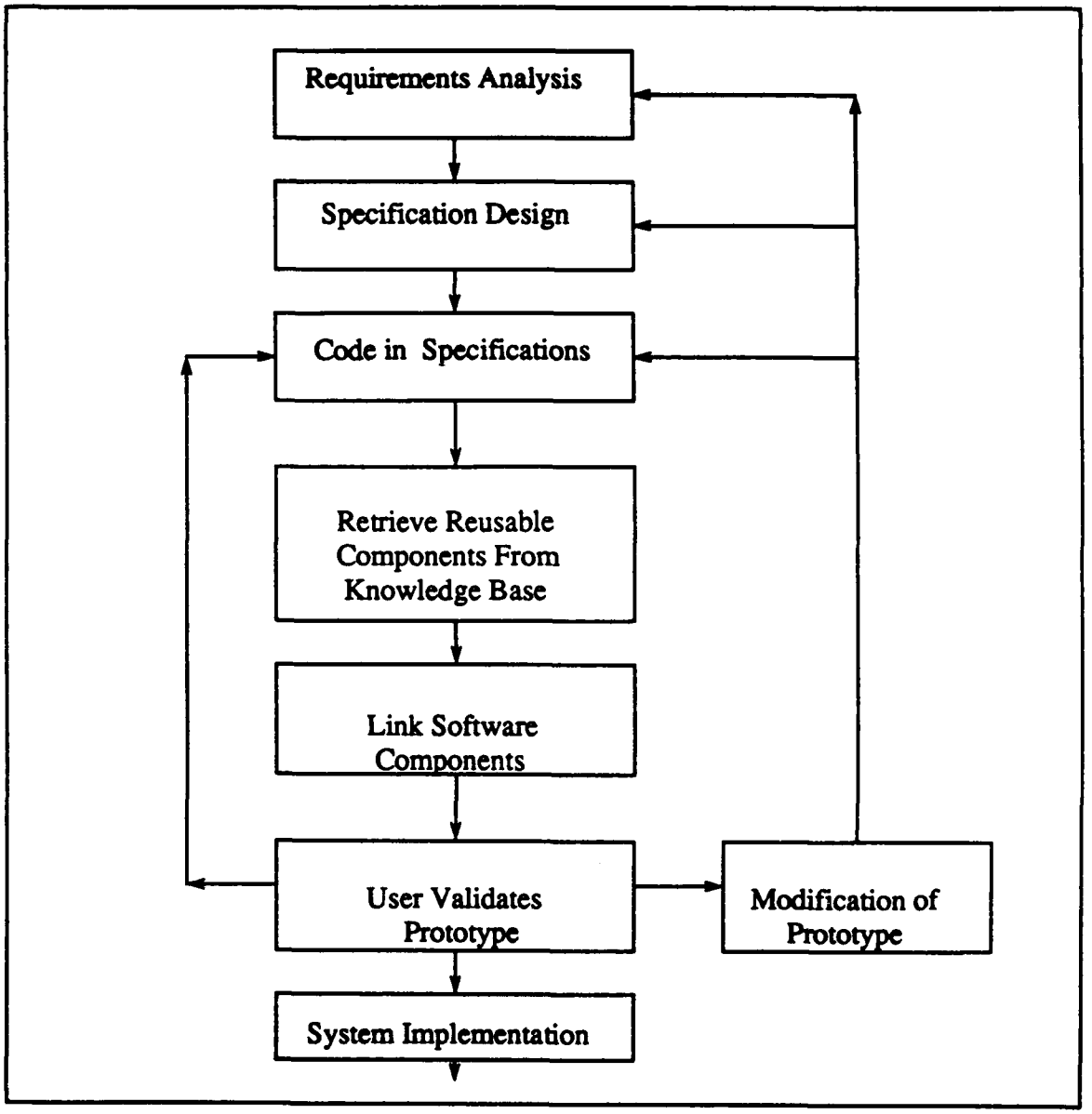


Figure 12. Reusable Software Methodology

was used, software synthesis referred to the automatic translating of assembly language into machine code (now called assembly). Later it referred to the translation of a higher-level language into machine code (now called compilation). Now it refers to the translation of very high-level languages (VHLL's) into machine code. As a designer, potentially even the user, recognizes the requirements; they are specified in some type of VHLL and the system is automatically synthesized. The focus of activity is in the simple specification of requirements and the installation and operation of the system. The design, coding, and integration activities would all be accomplished automatically. This methodology would have two dramatic effects: 1) development time would be greatly reduced, and 2) development costs would be reduced so much that adapting old systems would rarely be more cost-effective than re-synthesis of the entire system.

The automatic software synthesis methodology is very complex and currently not possible to implement. Since it is dependent on computer technology that is not currently available and since it features automatic code generation, it is unlikely that this methodology will be achievable any time soon. The rapid prototyping paradigm will possibly be instituted using one of the other methodologies, or a combination of two or more, and that automatic software synthesis will be the second or third generation of rapid prototyping.

2. Alternative Models

A model is a simplified description of a real world phenomenon. The models are usually more specific and detailed in their descriptions of how the methodology is to be implemented. There currently are only three published rapid prototyping models;

CAPS Rapid Prototyping Model [Ref. 8], IPS Software Process Model [Ref. 20], and the Generic (SDME) Model [Ref. 21].

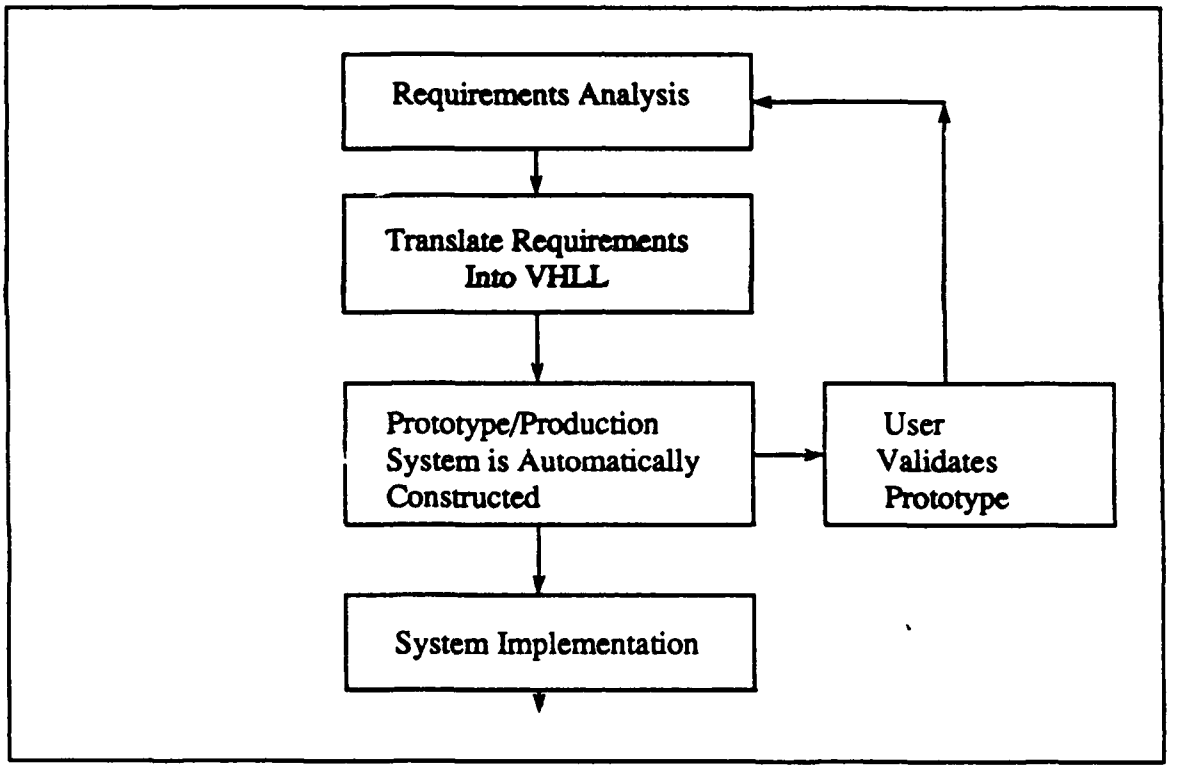


Figure 13. Automatic Software Synthesis Methodology

a. CAPS (Computer Aided Prototyping System) Rapid Prototyping Model

"CAPS, is being developed to improve software technology, and will aid the software designer in the requirements analysis of large real-time systems by using specifications and reusable software components to automate the rapid prototyping process". [Ref. 22: p. 66] The CAPS rapid prototyping model was initially based on the iterative prototyping model (Figure 14) [Ref. 23: p. 14]. The iterative prototyping model is similar to the incremental development methodology. More recent publication of the CAPS prototyping model reflects an integrated methodology consisting of

evolutionary and reusable software methodologies. The CAPS prototyping model is represented in Figure 15 [Ref. 22: p. 67].

CAPS has an extensive tools support system which is presented in Figure 16 [Ref. 23: p. 15]. The main subsystems of CAPS are the user interface, the software database system and the execution support system.

The user interface provides facilities for entering information about the requirements and design, presenting the results of prototype execution to the user, guiding the choice of which aspects of the prototype to demonstrate, and helping the designer propagate the effects of a change.

Dr. Luqi explains in [Ref. 23: p. 17] that the software database system consists of a design database, a software base, a software design-management system, and a rewrite subsystem. The design database contains the PSDL (Prototyping System Description Language) prototype descriptions for each software development project using CAPS. The software base contains PSDL descriptions and code for all available reusable software components. The software design-management system manages and retrieves the versions, refinements, and alternatives of the prototypes in the design database and the reusable components in the software base. The rewrite sub-system translates PSDL specifications into a normalized form used by the design-management system to retrieve reusable components from the software base.

Dr. Luqi describes in [Ref. 23: p. 17] that the execution support system contains a translator, a static scheduler, and a dynamic scheduler. The translator generates an executable framework that binds together the reusable components extracted from the software base. The translator's main functions are to implement data streams, control constraints, and timers. The static scheduler allocates time slots for

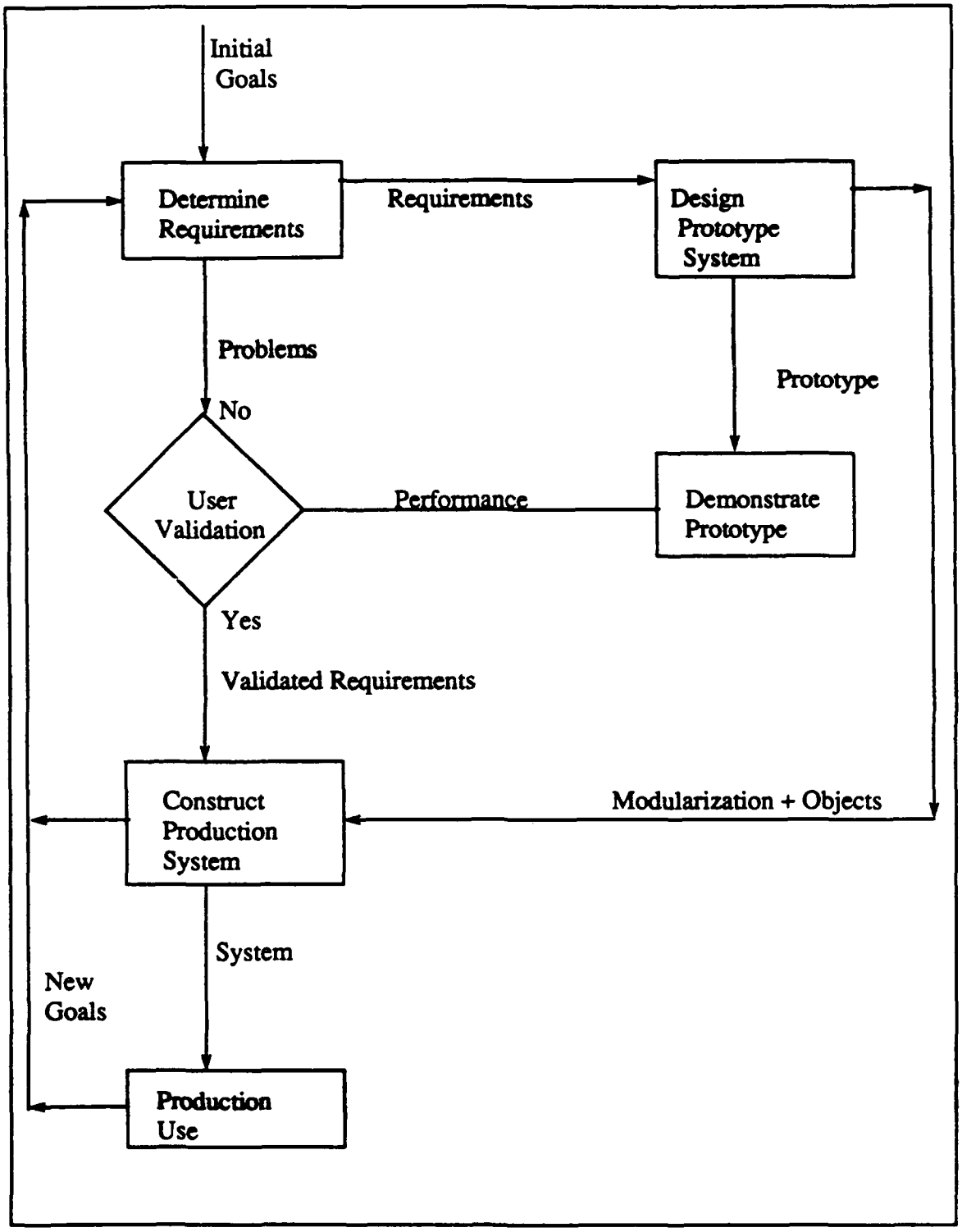


Figure 14. Iterative Prototyping Cycle

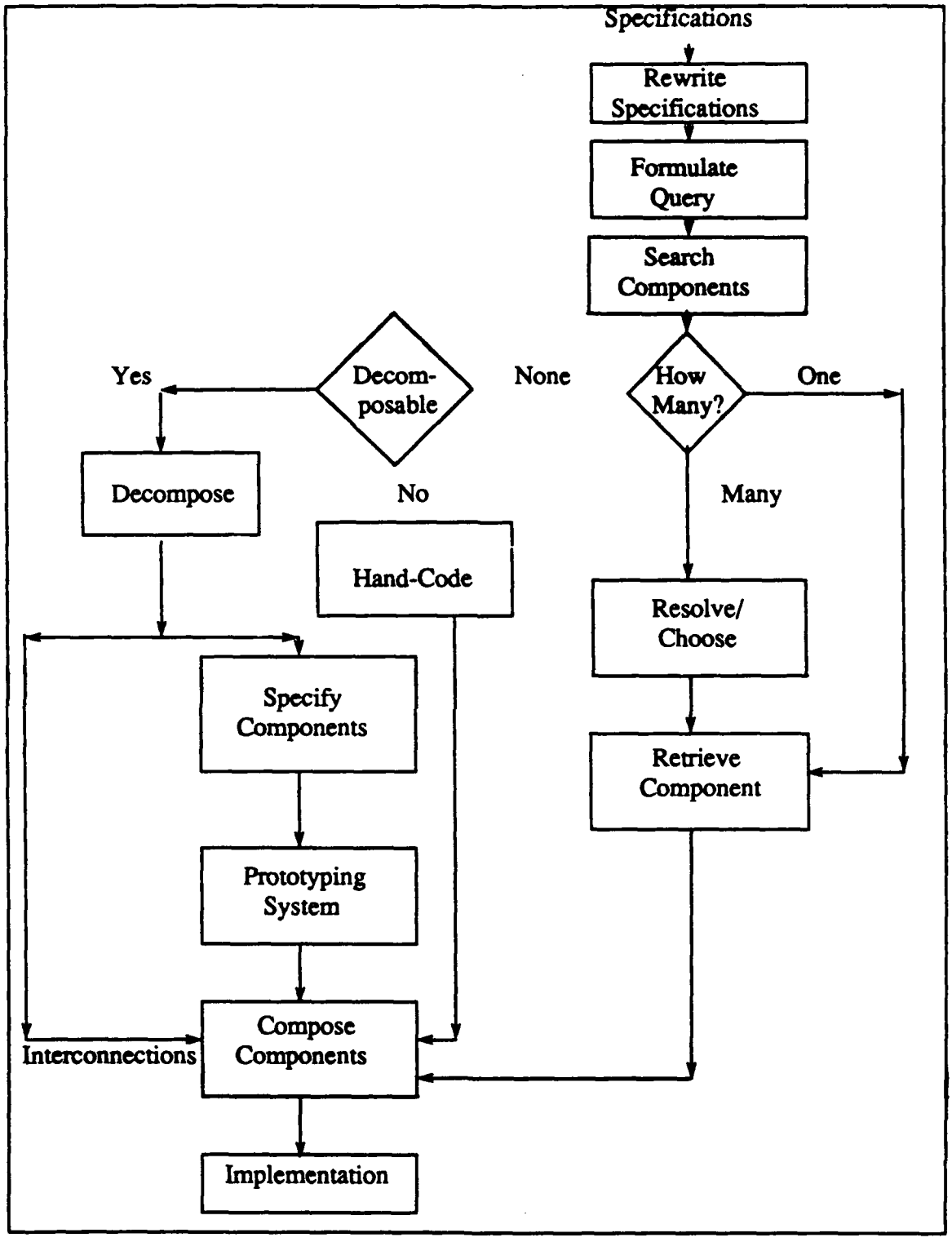


Figure 15. Prototype Development Using CAPS

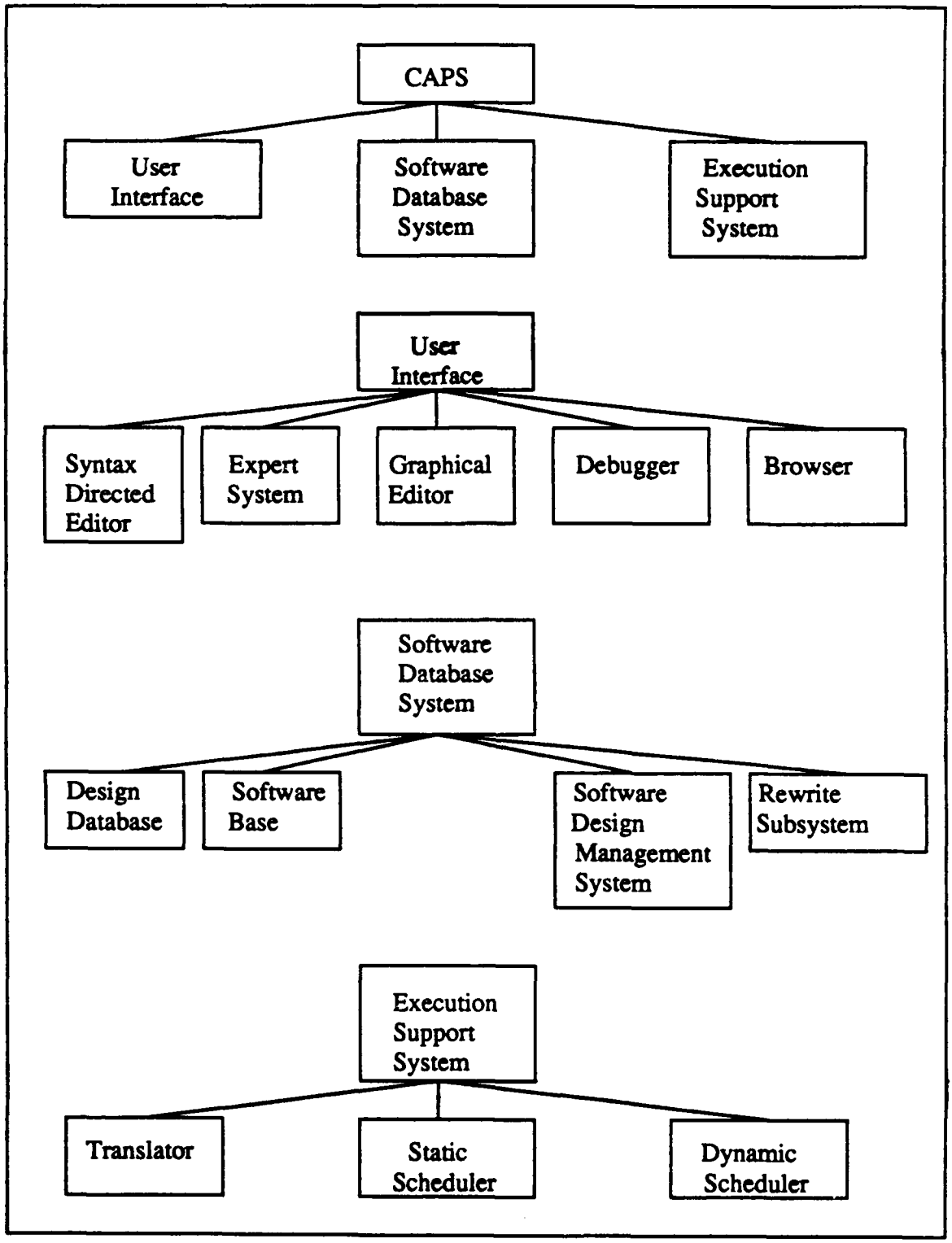


Figure 16. CAPS Tools Environment

operators with real-time constraints before execution begins. If the allocation succeeds, all operators are guaranteed to meet their deadlines, even with worst-case execution times. As execution proceeds, the dynamic scheduler invokes operators without real-time constraints in the time slots not used by operators with real-time constraints.

The Computer Aided Prototyping System is currently being developed and extensive research has been and is currently being conducted into all of the prototyping tools, the PSDL language, and evaluations of the system with regard to advancing computer technology. CAPS has been well documented in numerous publications, and is the most clearly defined model of the currently published rapid prototyping models.

2. IPS (Integrated Prototyping System) Software Process Model

The IPS Software Process Model is currently being researched and implemented at Southern Methodist University. The IPS model is based on the evolutionary and reusable software components methodologies. "The model differs from the traditional approach in that it concentrates on the hard problems of system development, namely; requirement specification and design rather than coding. Equally important, validation, evaluation, and hardware/software trade-off analysis are all part of the prototype development process". [Ref. 24: p. 10] The foundation for the model is depicted in Figure 17 [Ref. 24: p. 9].

The prototyping process is focused around the software design phase. The requirements analysis process does not change and the specifications phase changes only to support the increased activity in the design phase. "The IPS model replaces the software design phase of the traditional life cycle model with three phases: constructing a design, executing (testing) the design, and translating the design into a

high level language program". [Ref. 20: p. 1] The IPS model design phase is depicted in Figure 18 [Ref. 24: p. 10]. The main idea is if the software design can be tested and validated, then an automatic program generator would produce a high level language program from that design.

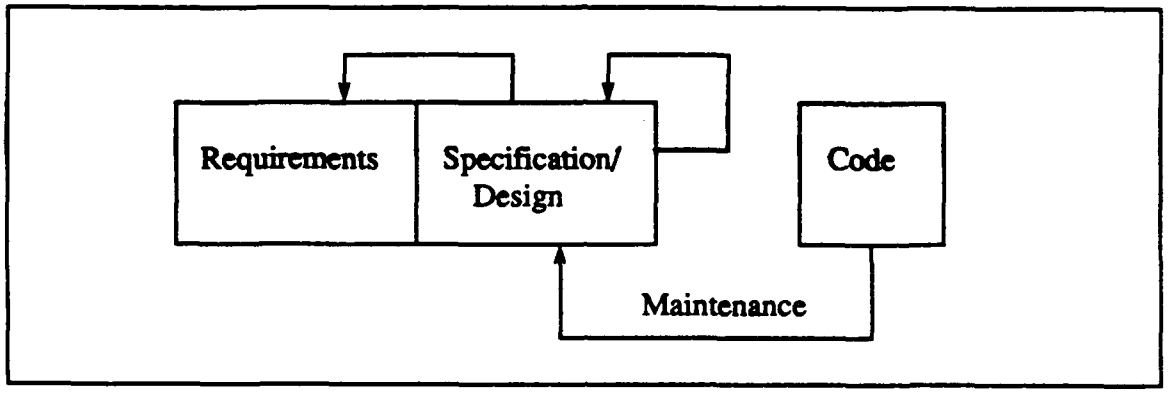


Figure 17. Process Model For Software/System Evolution

Yin and Tanik describe the ideal software design environment to support the IPS model in [Ref. 20: pp. 1-3]. The environment is depicted in Figure 19 and described below:

a. The uniform design representation: A good design representation is used for expressing design decisions precisely and the uniform form makes the design representation be capable as a medium integrating design construction, design testing, and design translation. The uniform design representation for this model is *Design Object Description Attribute Notation* (DODAN).

b. Static analyzer: The analyzer performs static dependency analysis of the software design, such as data dependency, control dependency, etc.

c. Executor (simulator/interpreter) : The main function of the executor is to expose the behavior of the software system being designed and to detect the

design errors. Exposing system behavior in the design phase can provide users and designers early feedback, reducing the cost of changes to implementation.

d. Automatic program generator : After testing the design, the desired high level language program can be automatically generated from the design, the design functionalities guaranteed to be reserved. Direct modification on code is not necessary.

e. Design component base : The design component base management stores and retrieves previously designed software components. Each design component in the base is described in the uniform design representation. The design component base management supports directly design maintenance and reusability.

f. User interface : The main function of a user interface is to provide communication between the designer and the design environment. The user interface offers the following facilities:

1. Design acquisition : The design acquisition consists of graphics tools and editors (user friendly editors). The editors cooperate with the multiple design representations and graphics tools, such as dataflow-oriented editor, state machine-oriented editor, language-oriented syntax-directed editor, etc. All these editors take different external design representations as inputs and convert them into the uniform design representation. The designer can choose an editor supporting the design methodology he is familiar with.

2. Testing display : The testing display shows the prototype execution or the interpretation of the design. The display may be a time chart indicating the system state changes or the desired system behavior like dialogue, input/output, etc.

3. Analysis display : The analysis display shows the results of the static analysis as the designer required.

4. Project output : The program generated based on the current status of the design can be retrieved by the designer.

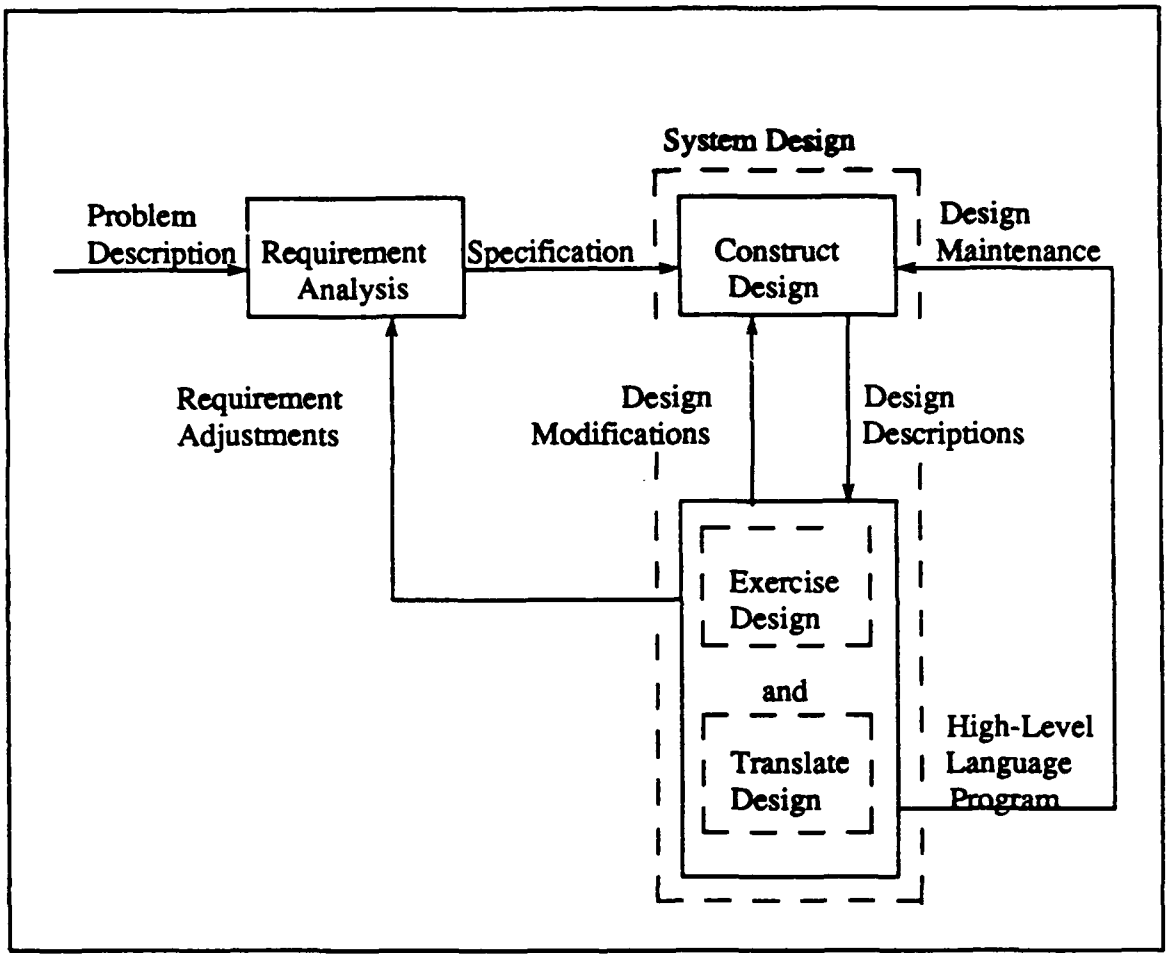


Figure 18. Detailed Process Model

The ideal software design environment, though purely generic, is a clear representation of what the authors envision as the necessary environment to support the IPS model. The same structural model, only reproduced with the IPS prototyping tools

and language replacing the generic descriptions are depicted in Figure 20 [Ref. 20: p. 5]. The IPS model environment is called *Design Activity Agent* (DAA).

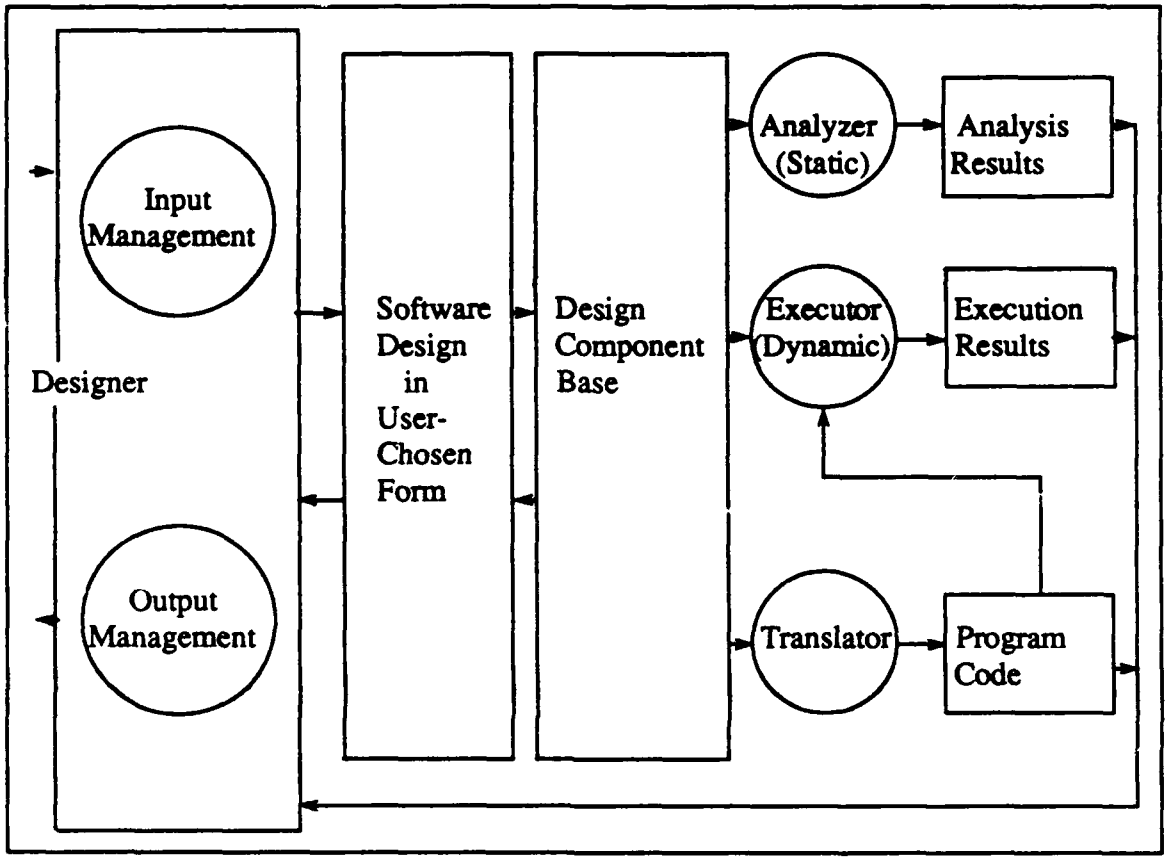


Figure 19. IPS Software Process Model Design Environment

The authors describe the components of DAA in [Ref. 20: pp. 3-4] and how they correspond directly with the generic descriptions depicted in Figure 19.

a. DODAN : DODAN is the uniform language used in DAA.

b. ART graphic window : This facility implements the analyzer.

c. Interpreter : This interpreter corresponds to the executor.

d. Ada specification generator : This is one of the instances of translators.

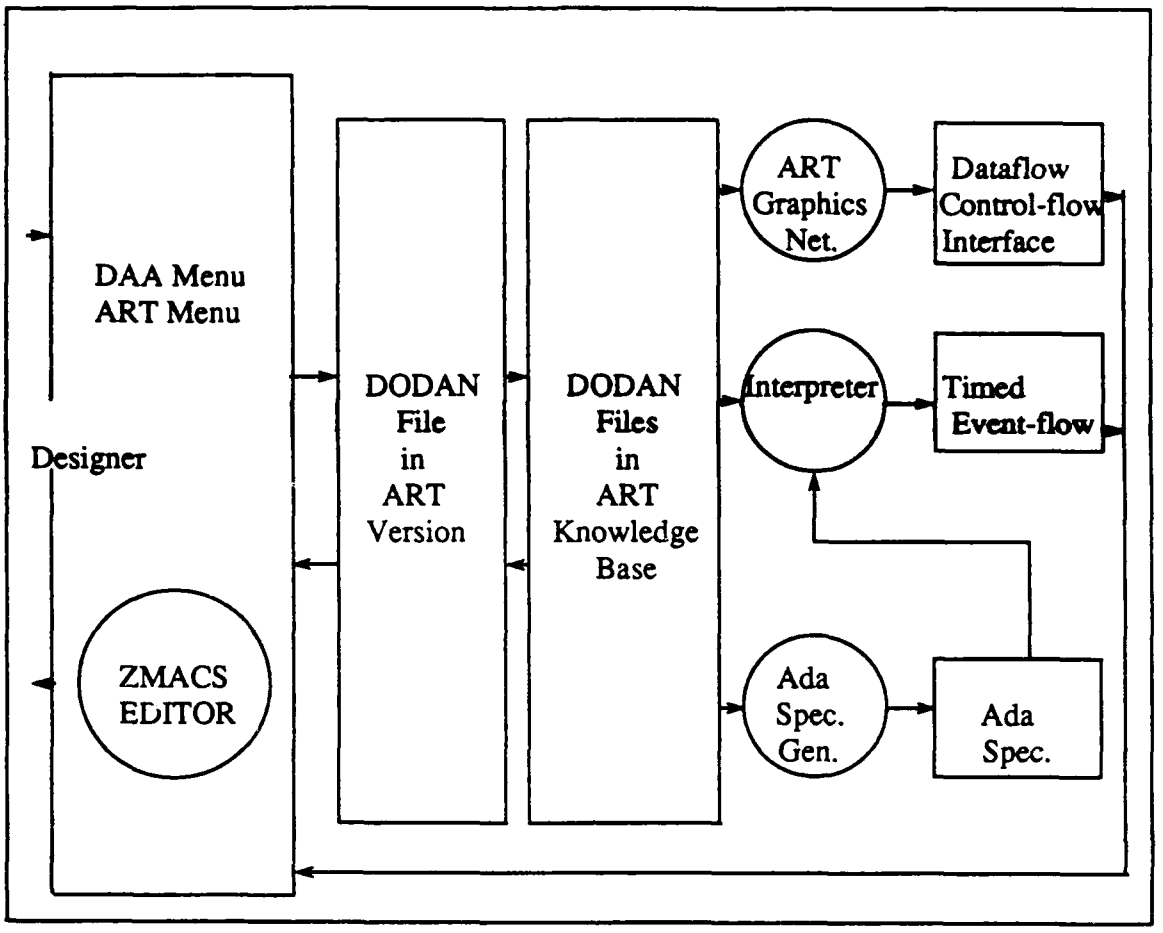


Figure 20. IPS Software Process Model Design Environment

e. ART knowledge base : This knowledge base implements the design component base.

f. User interface : The DAA window management combining with ART window management as well as the ZMACS editor constructs the DAA user interface.

The authors explain in [Ref. 25: pp. 1-3] that DAA allows the user to construct a software design in DODAN by using the ZMACS editor, save the design in a file, review, and analyze the design. DAA runs on *ART* (Automated Reasoning Tool) 3.0 installed on a Texas Instruments Explorer under software system 3.1. ART is a

software tool-kit for building expert systems, and has three major components: ART language, ART inference engine, and ART programming environment. The software information is represented in either frames or rules, the hierarchical structure viewed, manipulation of software information by firing rules, saving, and retrieving the software information.

The majority of effort expended thus far in research and implementation of the IPS model is focused on the design phase. The prototyping process is separated into two phases. The first phase is to prototype the design by using DAA, and then constructing a prototype using the automatic program generator. The design prototype process is explicitly defined in [Ref. 20] and [Ref. 25]. The process of how the executable prototype will be developed is still being researched and is not currently defined. It can be inferred from the description of DAA that a complete set of requirements could be prototyped since the transformation of design-level code to high level programming code is unlikely to be discriminant.

3. Generic (SDME) Model

The Generic (SDME) Model is based on the premise that there are few conceptual differences between the traditional Waterfall Life Cycle Model and the proposed rapid prototyping paradigm. Instead the two models are merely seen as different approaches to accomplishing the same end. The Generic Model is presented in Figure 21 [Ref. 21: p. 15].

The Generic Model divides the traditional Waterfall Model into generic phases. The development portion of the model consists of the generic phases, *analysis, design,* and *implementation.* The management and support functions are generally grouped independently as *maintenance, retirement, project management, and quality*

assurance. The development portion is further broken down into two domains, *problem* and *solution* (Figure 22) [Ref. 21: p. 15].

The generic structured development method is illustrated in Figure 23 [Ref. 21: p. 15]: the primary work flow occurs from left to right. Analysis is a decomposition process. Basic objects and transforms are defined in the problem domain. Then these objects and transforms are decomposed to a sufficient level of specificity that allows the desired behavior within the problem domain to be defined. "Each method has a different approach towards developing the set of symbols with which to define the problem, but the methods all converge on several classes of generic deliverables at the end of the analysis". [Ref. 21: p. 15]

Tyron points out in [Ref. 21: p. 15] that all development methods deliver some form of a static model of the problem domain which describes and defines the objects and the relationships within the problem domain. Analysis also creates a dynamic model which describes the permissible behavior of the objects within the problem domain. The behaviors or transforms are also defined in terms of the symbols developed in the static model. Examples of portions of the dynamic model are data flow diagrams and state transition diagrams.

Tyron claims in [Ref. 21: p. 16] that design is a process of architecture and synthesis. Design takes the products of analysis, the static, dynamic, and constraint models, and attempts to build a class of solutions to the defined problem. It represents the point of shift from a problem-oriented perspective to a solution-oriented perspective .

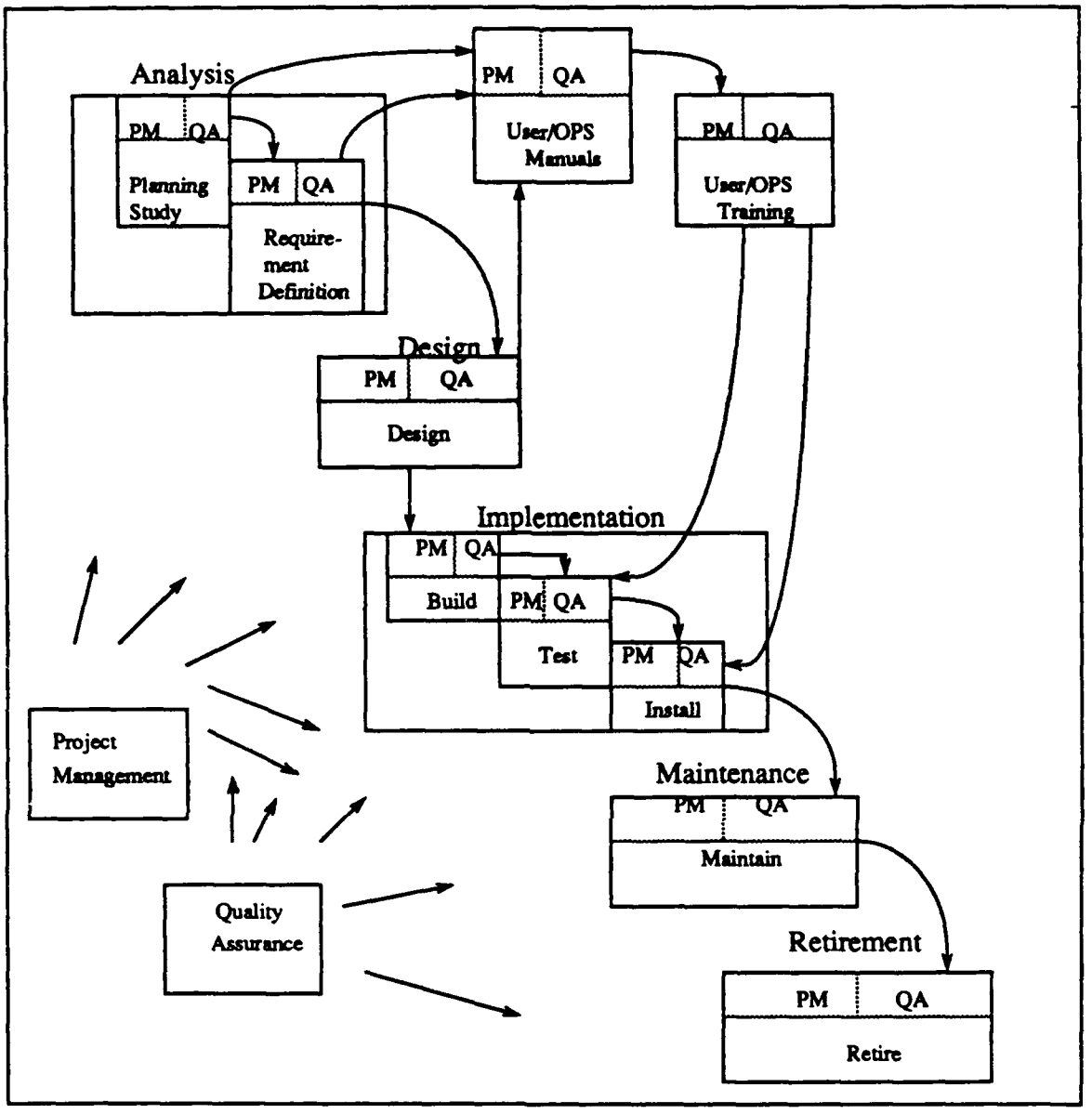


Figure 21. Generic Life Cycle View of The SDME

Tyron explains in [Ref. 21: p. 16] that design consists of the activities that yield a template for the implementation of the problem. These activities are the creation of a general system architecture of design. This framework must be of sufficient strength to handle both the dynamic and static models yet satisfy the requirements of the constraints model. These activities occur either in sequence or concurrently

depending upon the method. Once the overall design architecture is chosen, the task of design is to distribute the static model into the architecture. The dynamic model is mapped onto the distributed static model in a way that best meets all of the restraints found in the constraint model.

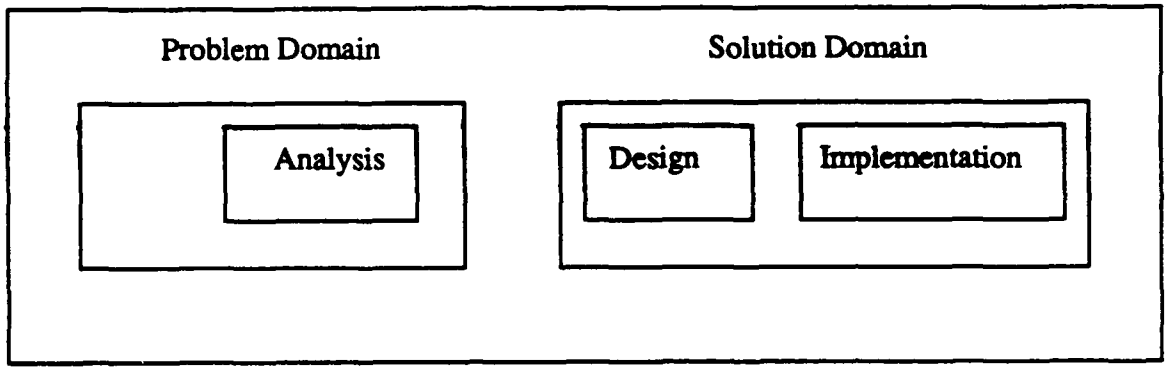


Figure 22. Problem vs. Solution Orientation

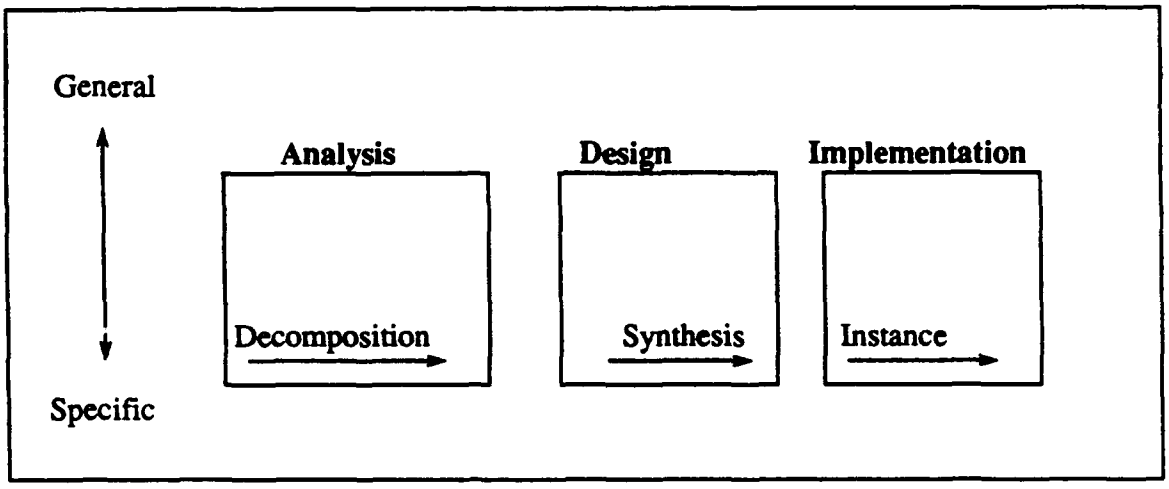


Figure 23. Generic Development Flow

Tyron mentions in [Ref. 21: p. 17] that implementation takes the various "pieces" of the design and builds them using actual devices (e.g., languages, hardware, operating systems, DBMS's, etc.). The system is an instance of the design. The system is then tested to ensure that its actual behavior is within the acceptable

deviation from the desired behavior. The tested system is then put in place within an organization accompanied by the appropriate training of the users.

The generalization process of going from general to specific, or from specific to general, is one of the description tools that the author of [Ref. 21] uses to explain the similarities and differences between the traditional model and the iterative prototyping model. In the traditional model (Figure 24), the software development process fluctuates between generality and specificity. The iterative prototyping model (Figure 25), displays a more fluid transition through the development process, but never gets very specific. If the requirements are vague, then the lack of specificity allows the stated requirement to match up closer to the implemented requirements. If the requirements are clear and concise, the semi-specific implementation will not reflect the stated requirements. To account for the different conditions, a *hybrid model* (Figure 26) is presented. "The hybrid model basically starts out with an iteration of a prototype in order to clarify the desired behavior and then proceeds into the traditional model". [Ref. 21: p. 17] The strategy of how the transition occurs from the process to the traditional model is not discussed. The methodology of how the prototypes are to be built is not discussed either. It appears that the Generic (SDME) Model is attempting to use a version of the rapid throwaway methodology to enhance the requirements engineering process.

E. SUMMARY

The rapid prototyping paradigm offers many advantages to the software development process. Throughout this chapter, we have highlighted the major advantages, as well as some of the complex issues that are still being researched. The survey of

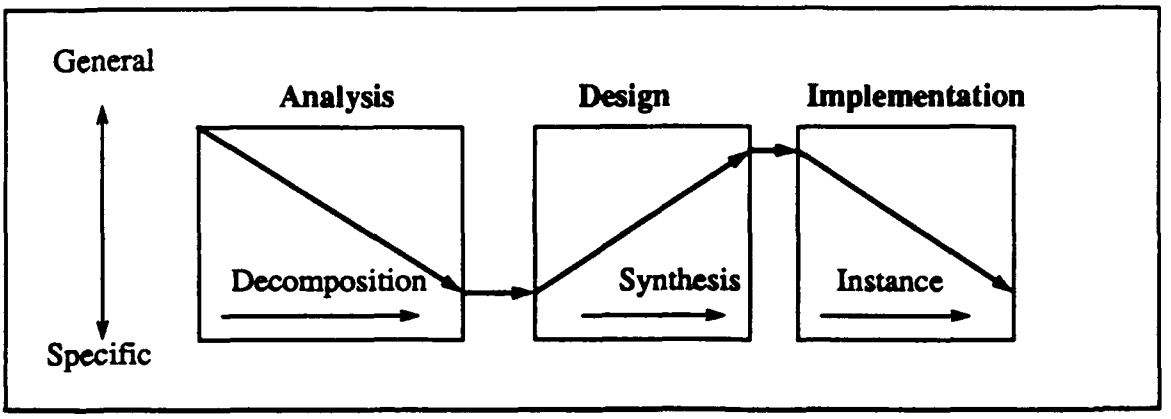


Figure 24. Waterfall Model Strategy

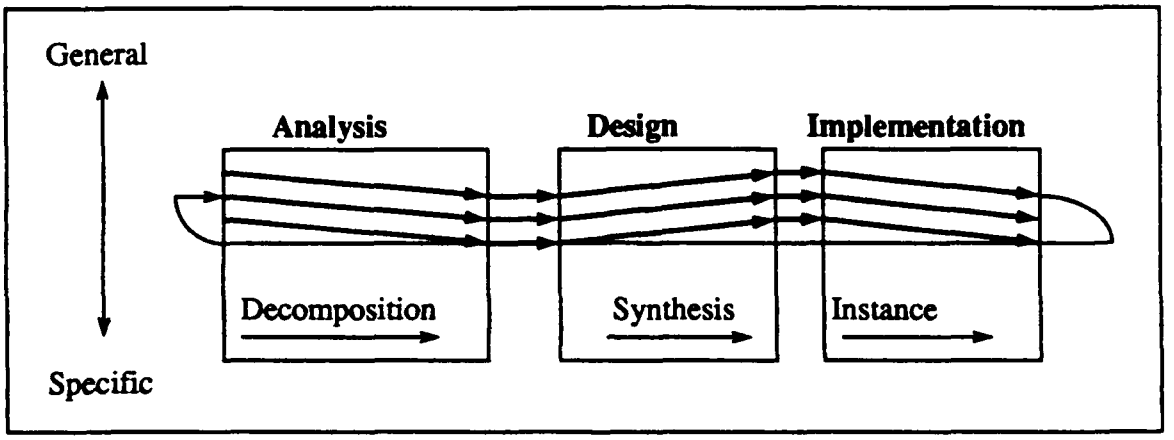


Figure 25. Iterative Prototyping Model Strategy

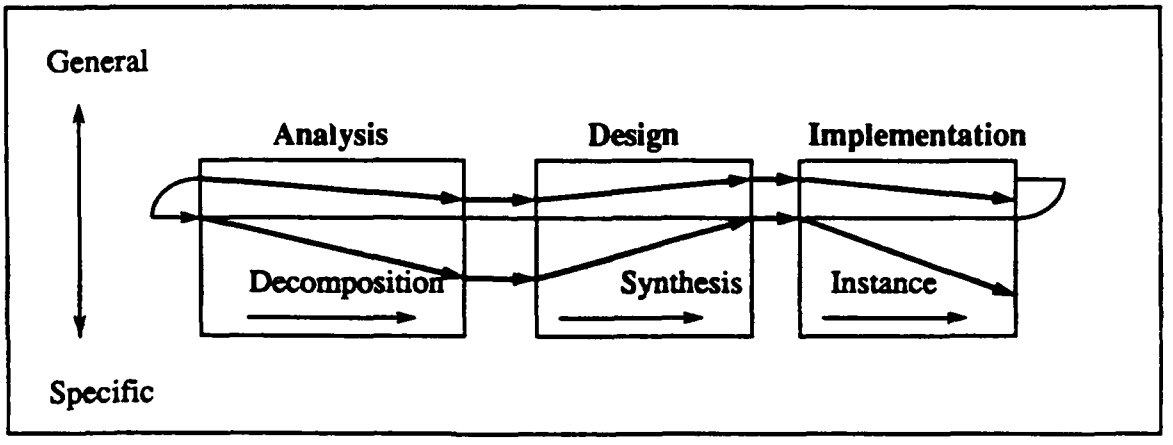


Figure 26. A Hybrid Strategy

the methodologies revealed a progressive means of implementing the rapid prototyping paradigm. Some of the methodologies are capable of being implemented now, while others require more research and advances in technology to permit implementation. Two of the surveyed rapid prototyping models, CAPS Rapid Prototyping Model [Ref. 8] and IPS Software Process Model [Ref. 20], display conceptually similar design features, while the Generic Model [Ref. 21], is more conventional in its approach. The survey of the models revealed that regardless of how diverse the approaches are to implementing rapid prototyping, they all require more research and are "slow" in development.

III. EVALUATION OF PROPOSED RAPID PROTOTYPING METHODOLOGIES

Since the rapid prototyping paradigm is still relatively new , an evaluation of alternative software life cycle methodologies and models is necessary for a few reasons. One reason is to determine if recent research proposals fulfill the requirements and goals of the new paradigm. Another reason is to determine what is achievable now and what will be achievable with future advances in computer technology. The third reason is to provide a baseline from which recommendations can be made on how to manage rapid prototyping to meet DoD's software development needs. It should be noted that these reasons are not an exhaustive list, but do capture the intent of this thesis.

The evaluations of the methodologies and models require different evaluation criteria from each other. The evaluation criteria for the methodologies will be focused on how well they meet the strategic goals of the proposed paradigm. The evaluation criteria are 1) *prototype development, 2) use of reusable software components, 3) evolutionary prototype production, 4) meeting user needs, 5) time, activities, and effort, and 6) implementation outlook.* Some of the evaluation criteria for the methodologies cannot be evaluated because there are no detailed descriptions.

A. EVALUATION CRITERIA DESCRIPTIONS

Prior to evaluating the rapid prototyping methodologies, the evaluation criteria need to be more clearly defined . Since the methodologies are strategic descriptions of how

to implement the new paradigm, the evaluation criteria is focused on their respective design features.

Prototype development : This criterion addresses the efficiency with which the prototype is constructed and the effect the prototype has on requirements engineering. This criteria also addresses the effect the methodology has on the ability of users to validate the stated requirements as well as the changing requirements.

Use of reusable software components : This criterion addresses whether the methodology encourages the use of reusable software components in its prototype construction. The criteria also addresses whether the production system is manually coded or whether the use of reusable software components encouraged.

Evolutionary prototype production : This criterion addresses whether the developed prototype results in a production system or is used primarily for the purpose of validating requirements in the requirements engineering process.

Meeting user needs : This criterion evaluates how well the methodology meets user needs with respect to on-time delivery and meeting the user requirements. This approach to evaluating the methodologies was presented in [Ref. 5] and [Ref. 7]. The experimental data to support this evaluation is anticipatory rather than factual, but it does provide an interesting perspective on how the methodologies might perform in relation to user needs.

The user needs are evolutionary and increase over time. A representation of the user's needs is presented in Figure 27 [Ref. 5: p. 1455]. The authors note in [Ref. 7: p. 4] that although these needs are shown as a linear function, in actuality, the function is neither linear or continuous. The time scale on the x-axis should be

assumed to be non-uniform, containing areas of compression and decompression, and the units on the y-axis are assumed to be some measure of amount of functionality .

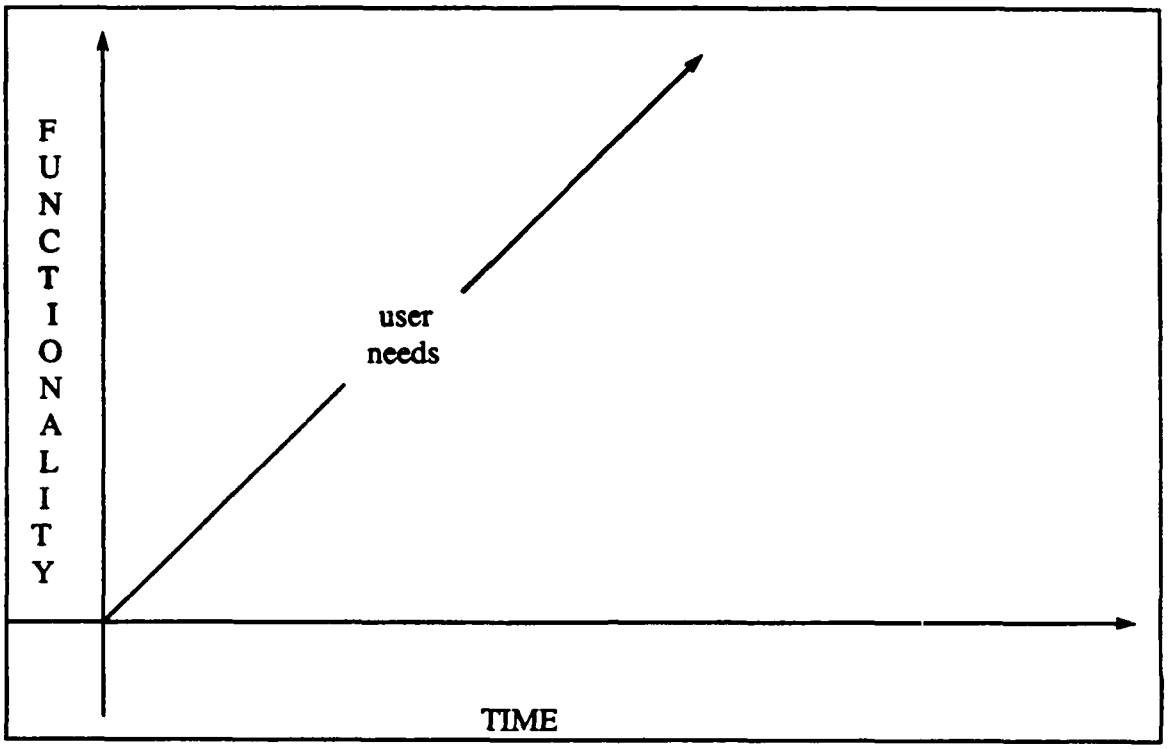


Figure 27. Evolution of Stakeholder Needs

Figure 28 [Ref. 5: p. 1455] depicts what happens during software development using the traditional life cycle model. The authors explain in [Ref. 7: p. 4] that at time t_0, the need for a software system is recognized, a requirements baseline is established, and a development effort commences. At time t_1, the development effort has produced an operational product, which satisfies neither the current t_1 needs (evolved from baseline t_0 needs), nor the old t_0 needs due to poor understanding or misinterpretation of those needs during implementation. The product undergoes a series of enhancements (between times t_1 and t_3) which eventually enable it to satisfy the

original t_0 requirements (at t_2) and then some. Ultimately, at time t_3, continued enhancement is no longer cost-effective and the decision is made to build a new system. The cycle repeats itself with the establishment of a new requirements baseline at time t_3, and the initiation of a new development effort, to be completed at time t_4 .

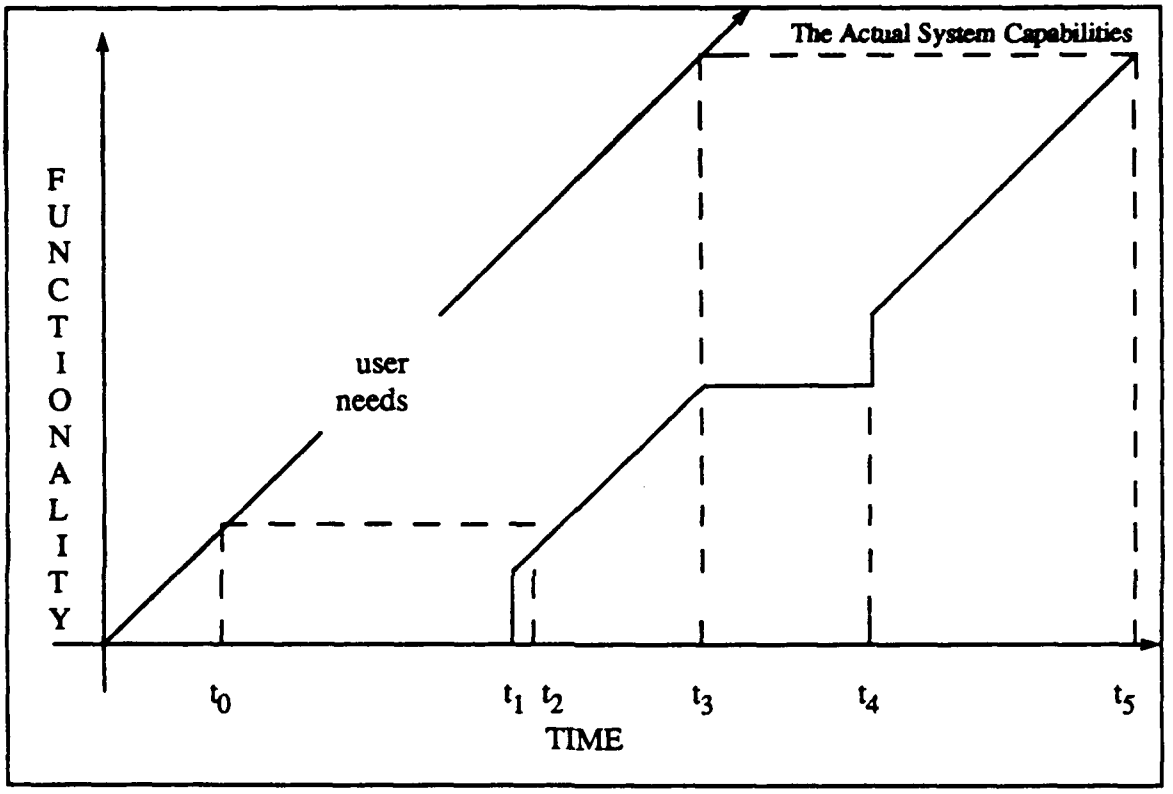


Figure 28. System Functionality Shortfall

The authors point out in [Ref. 7: p. 4] that several useful metric's for comparing and contrasting development methodologies have been derived from this depiction of user's needs versus systems capabilities. These metrics are portrayed graphically in Figure 29 [Ref. 5: p. 1456] and are described below :

Shortfall - A measure of how far the operational system at any time t, is from meeting the actual requirements at time t.

Lateness - A measure of the time that elapses between the appearance of a new requirement and its satisfaction. Of course, recognizing that new requirements are not necessarily implemented in the order in which they appear, lateness actually measures the time delay associated with achievement of a level of functionality.

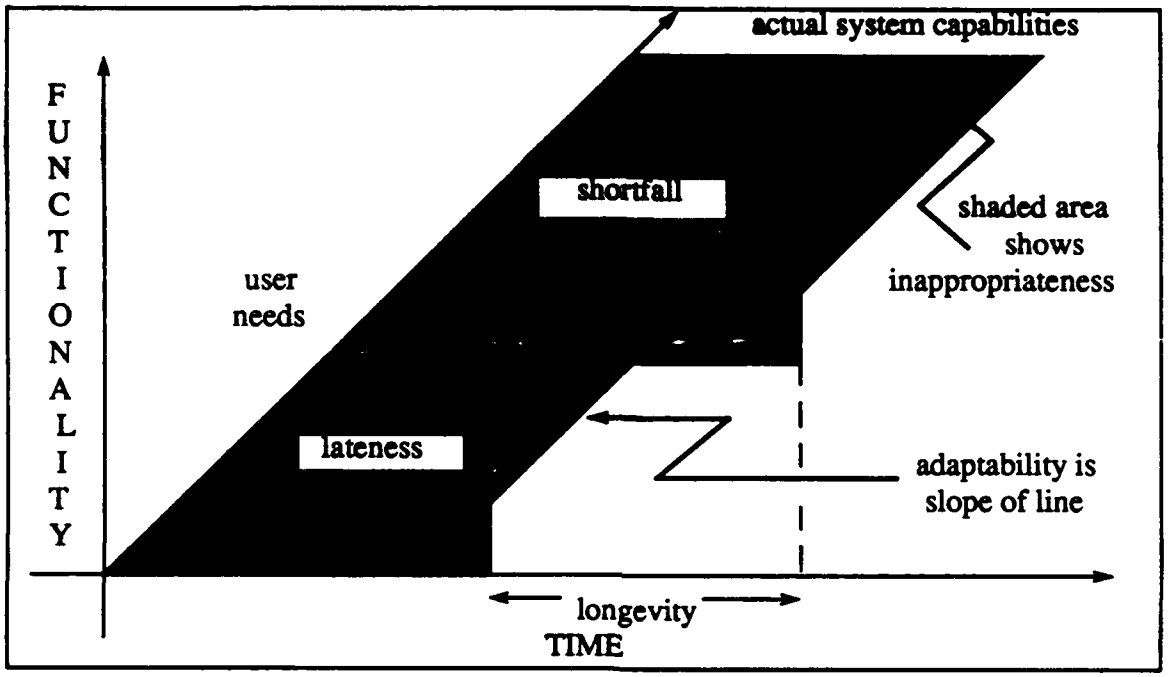


Figure 29. Development Methodology Comparison Metrics

Adaptability - The rate at which the software solution can adapt to new requirements, as measured by the slope of the solution curve.

Longevity - The time during which a system solution is adaptable to change and remains viable, i.e. the time from system creation to system replacement.

Inappropriateness - The shaded area between the user needs and the solution curves, and thus captures the behavior of shortfall over time. The ultimately "appropriate" model would exhibit a zero area, meaning that new requirements are instantly satisfied.

Time, activities, and effort : This criterion evaluates a three-dimensional view of the software development process with respect to time, activities, and effort expended. This evaluation criteria was also presented in [Ref. 5] and [Ref. 7]. It too lacks the experimental data, but the essence of the evaluation focuses on each stage of development.

In the traditional life cycle model, the step-by-step or stage-by-stage refinement process gives the impression of being one-dimensional and oriented only on time. Figure 30 provides a single dimension view of the traditional life cycle model [Ref. 7: p. 2]. "This one-dimensional interpretation has been carried forth into DoD software development standards, industry standards, technical writings, reference books, and attempted application to software projects". [Ref. 7: p. 2] The problem with a one-dimensional view of software development is that the dynamic nature of the process is not necessarily a step-wise refinement. Each phase or sub-process, which is inherent to any of the methodologies, remains ongoing throughout the process until the software is retired or replaced.

To better see the overlapping of the phases or sub-processes, a two-dimensional perspective of the software process is helpful. Figure 31 shows a two-dimensional view of the traditional life cycle model [Ref. 7: p. 2]. The activities and time perspective on two adjacent axes provides a clear perspective of how the different activities interact and the relationships between these activities and time. The shaded areas represent the activity in each stage with respect to time.

The authors claim in [Ref. 7: pp. 2-3] that by using this model, other activities such as planning , quality assurance, configuration management, and test and evaluation, that occur during a systems lifetime can be more appropriately labeled.

The following are some suggested stages: definition, development, and operation/maintenance. It is important to understand that there is not always a clean demarcation between stages. For instance, there is normally a period at the end of the development when the system is being installed, modified, and accepted. In the case of multiple site installation, this deployment period may take several months or even years. The first system installed may be in operational use long before the last system is delivered. Thus, there is an overlap between the beginning of the operation/maintenance stage and the end of the development stage.

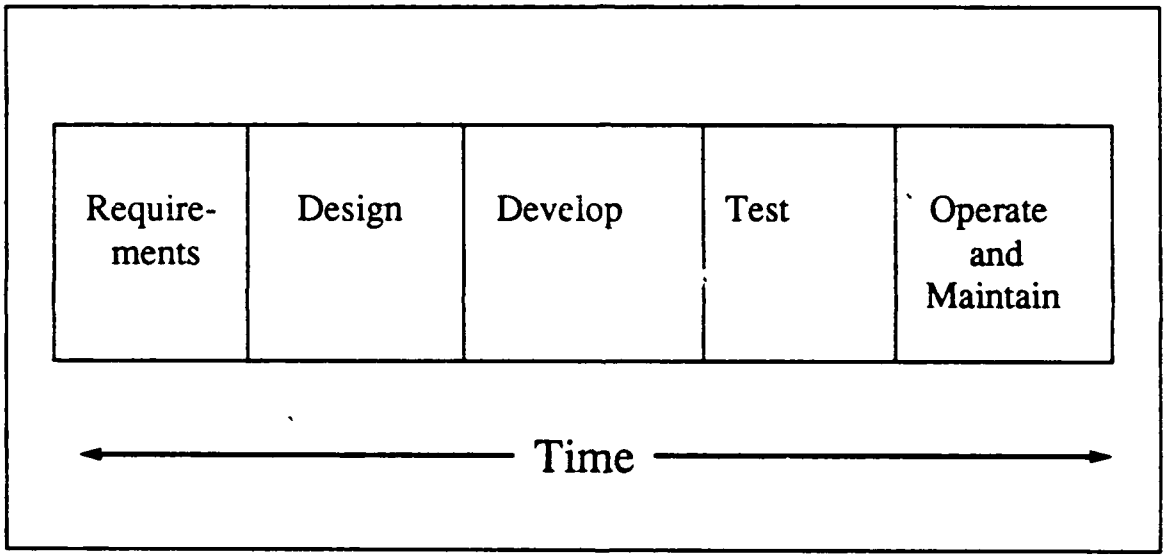


Figure 30. Single Dimensional View of the Traditional Life Cycle Model

The authors explain in [Ref. 7: p. 3] that this two-dimensional view of the life cycle helps depict the overlapping and continuous nature of software development related activities. However, understanding the interrelationships and interactions of the activities is difficult without some depiction of the level of effort required for each activity relative to time. This third axis (dimension) depicts the "effort" needed to complete the model. Figure 32 depicts this third dimension with only the "concept of

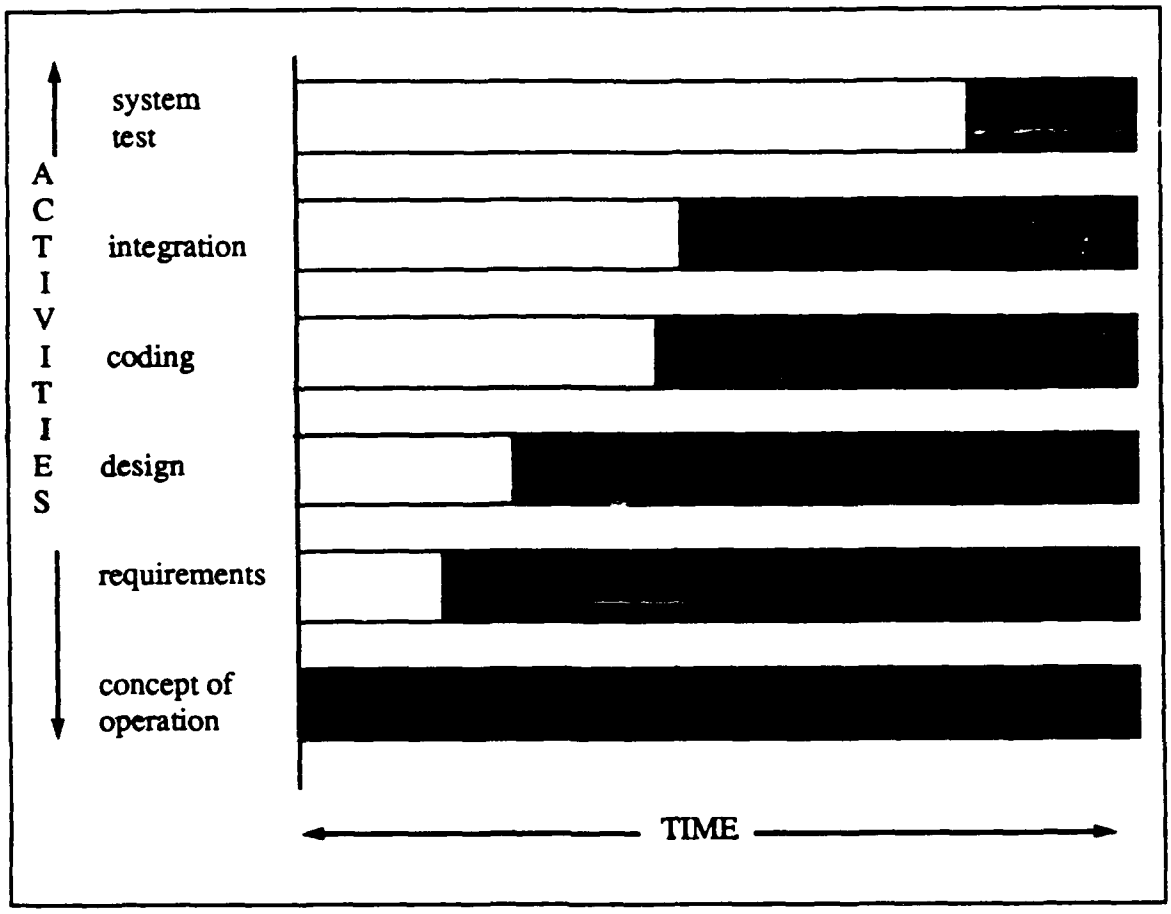


Figure 31. Two-Dimensional View of the Traditional Life Cycle Model

operations" activity completed. This depiction is not representative of any particular project; however it attempts to point out the reality of software development. The activity level for "concept of operations" is highest in the definition time frame, dropping off as the RFP is released and proposals are prepared. The activity level normally increases during the development in parallel with the system requirements reviews and software design reviews when additional insight is provided into the actual system and a rethinking of the concept of operations occurs. This increase normally occurs again during the system acceptance testing and then periodically throughout the operation and maintenance of the system.

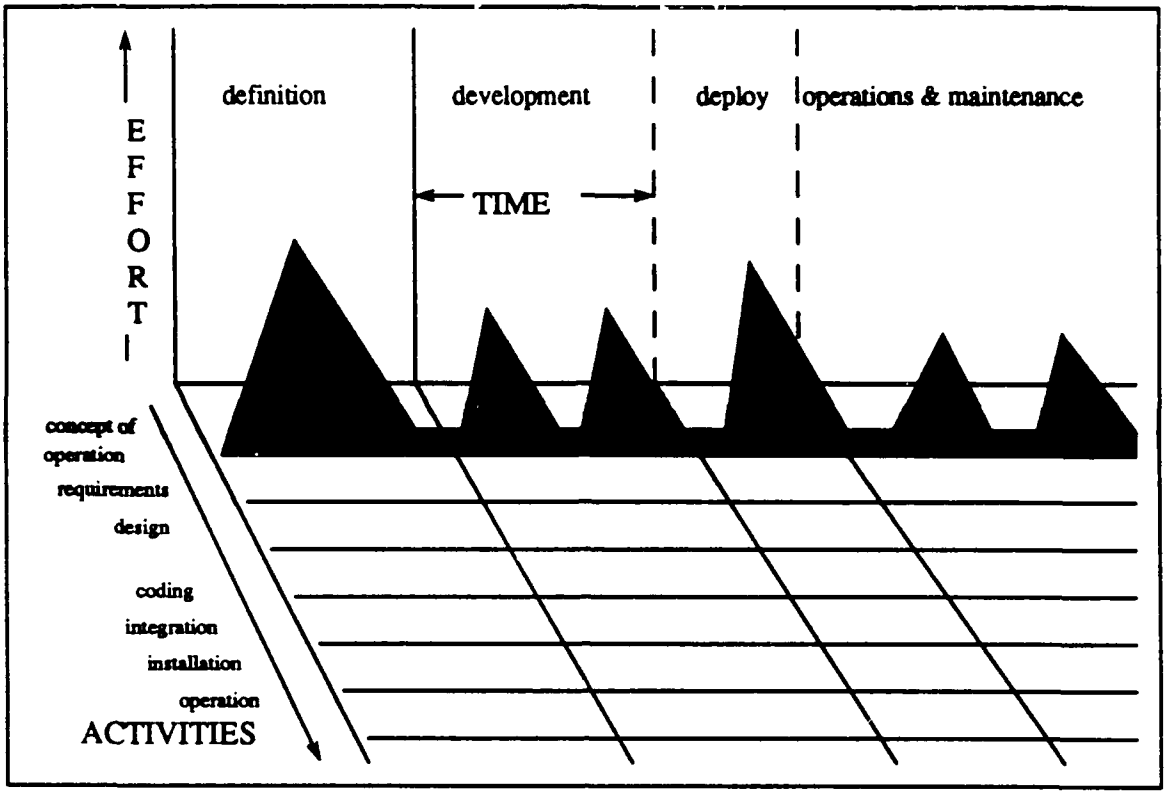


Figure 32. Third Dimensional for Effort Added to Model

This three-dimensional view of the software development process with the proposed rapid prototyping methodologies will provide a clearer perception of just how much effort is expended compared to the traditional life cycle model. The actual three-dimensional views may be revised once the methodologies are implemented in a model, or if the methodologies are integrated. If two or more of the methodologies are integrated, the three-dimensional view should show some improvements.

B. RAPID THROW-AWAY PROTOTYPE METHODOLOGY

1. Prototype Development

The "quick and dirty" partial implementation (prototype) of the system provides a tool to facilitate one facet of requirements validation. The prototype allows the user

to validate a partial set of the requirements. The construction of the prototype is not as well defined, which leads to some concerns about the usefulness of the methodology.

The authors in [Ref. 7: p. 5] claim that the requirements engineering process differs slightly from the traditional life cycle model in that the prototype is constructed to allow the user the opportunity to validate some of the requirements early in the software development process and give the developers the confidence that they are building the "right" system.

The partial set of requirements would imply that a small-scale prototype, one which represents user-interface features and possibly limited implementation features, would meet the intent of the methodology. However, it was noted in Chapter II that the more complex a system gets and the more interactions between major functions and modules, the more susceptible the system is to rippling effects. With this in mind, there are concerns over whether the prototype will truly represent the system as it will look and act upon implementation. Surely, the prototype will be unable to represent the real-time constraints of the system. Therefore, the usefulness of this prototyping methodology for large real-time systems is suspect.

Given a small-scale system, or a simple large scale system in which implementation is not very complex, the methodology could be useful. The rapidly constructed prototype would allow users to validate whatever requirements they feel are most important. If the users are concerned about user-interface features (i.e., screen displays, windows, icons, etc.), then the prototype could serve as a useful validation tool.

If the user wants a prototype of a complex requirement or a representation of an integrated set of requirements, then the prototype does not make much sense. The prototype is only a partial version of the system, therefore it is not detailed enough to give users a true representation of performance. Another aspect is that the prototype is not used in the production system, and designers would rather devote the time to coding the complex requirements than in developing a partial prototype. So for small-scale systems or dominant user-interface systems, the methodology has some merit. Given a clear and concise set of requirements that would remain static over the period of development, then the rapid throwaway prototype is useful. But as discussed in earlier chapters, this is a rarity rather than the norm.

The discussion of the home building industry in Chapter II probably best explains this methodology. The small-scale model that architects and designers construct is to allow potential home-owners the opportunity to see what the home will look like when completed. The scaled down model is not detailed to the point of showing every feature, but only features that the architects feel are most important to the potential home-owners. Another similarity is that none of the model will be used to construct the house. If the potential home-owners want a different style roof or front window, the architect will note the enhancement and include it in the design of the home. But neither the restructured roof or front window of the model will go onto the constructed home. Once the scaled-down model is approved, the changes to the architectural plans are made and the model is not used again. A similar process is used in this methodology where the scale model corresponds to the prototype, the architect corresponds to the software designer, and the potential home-owners with the users.

2. Use of Reusable Software Components

The methodology of constructing a "quick and dirty" prototype assumes that the prototype could be manually coded. The methodology does not treat reusable software components as a necessary feature. However, if reusable software components were utilized in the construction of the prototype, then the "quick" part of the process would be enhanced. Since none of the code from the prototype will be used in the production system, the often confusing task of translating previously written code is not a problem.

It would be very inefficient to spend the time manually coding the prototype, and then not use it again as production coding. So if this methodology is to be utilized and be as efficient as possible, the use of reusable components would appear to be a necessary enhancement.

3. Evolutionary Prototype Production

The title of this methodology implies that evolutionary prototype production is not an issue. The prototype is not intended to be used beyond the requirements analysis phase of the requirements engineering process. This may seem inefficient considering the entire software development process, but it does enhance the requirements engineering process of the traditional life cycle model. Unfortunately, because it is not evolutionary, the problem of the dynamic stages that software development go through, the enhancements gained early in the process could be overrun by the changes later in the process.

4. Meeting User Needs

This methodology makes some strides in closing the gap of "inappropriateness" in the traditional life cycle model. Figure 33 represents the theoretical gap between

user needs and rapid throwaway methodology [Ref. 7: p. 6]. The authors explain in [Ref. 7: pp. 5-6] that the rapid prototype itself is shown as a short vertical line proving limited and experimental capability soon after time t_0. It is not connected to the "system" functionality line, as it is thrown away. However, use of the prototype leads to a clearer understanding of the requirements sooner than the traditional written requirements specification method. Therefore greater functionality can be delivered sooner than with the traditional approach. There is no reason to believe that the use of the rapid prototype alone will increase the length of time during which the product can be efficiently enhanced without replacement. Therefore, this period of time for evolution or enhancement of the rapid prototype-based development (e.g., t_1 to t_3) is the same as for the traditionally developed product. When the system

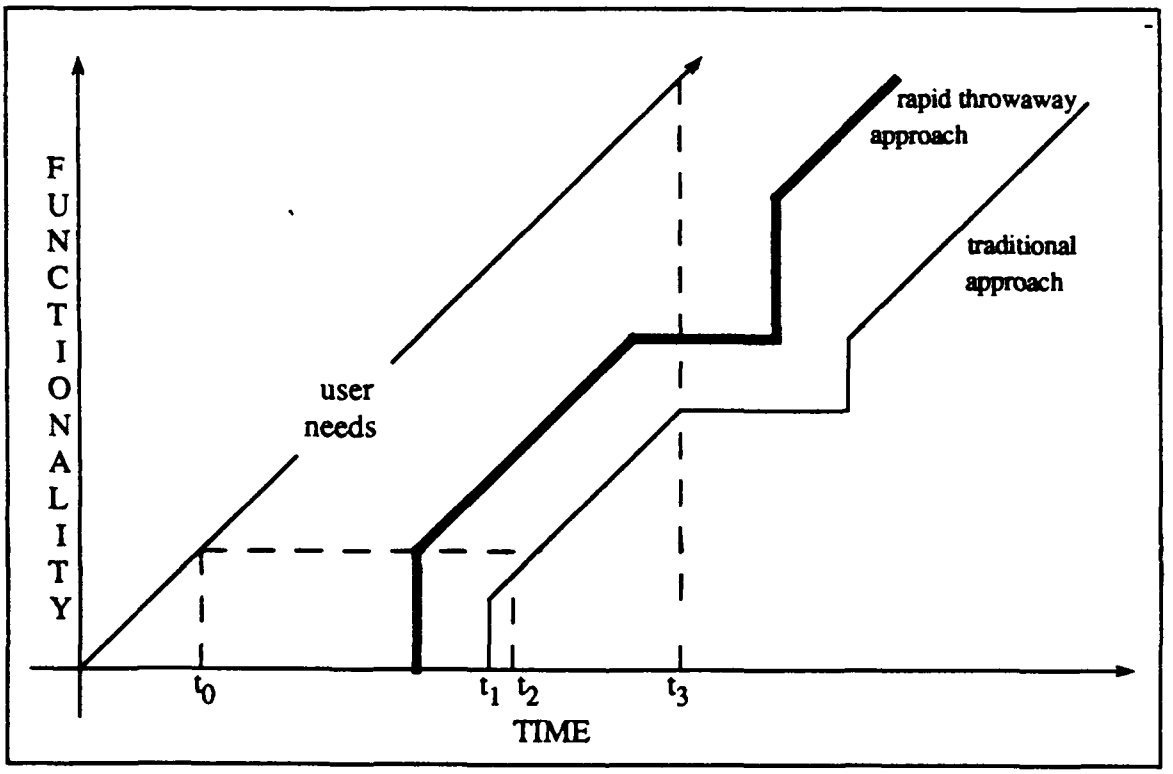


Figure 33. Rapid Throwaway Methodology vs. Traditional Life Cycle Model

is replaced, use of the rapid prototype can again be delivered sooner, having the overall effect of decreasing the area of "inappropriateness".

5. Time, Activities, and Effort

The three-dimensional representation of the rapid throwaway methodology is depicted in Figure 34 [Ref. 7: p. 5]. The significant efforts in the early stages of each phase contribute primarily to the development of the prototype. The leveling off of effort across all the stages is mostly a result of the validated requirements from the prototype and the designers having a better understanding of what the user "really" wants.

The authors claim in [Ref. 7: pp. 5-6] that the effort expended in this methodology appears to be greater than with the traditional life cycle model. The additional effort of up-front stages reflects the fact that the prototype is manually coded. The increased effort following the validation is slightly more than with the traditional model because the system needs to be re-coded and the requirements that were validated from the prototype must be more strictly met. Although the effort expended is greater both in prototype development and in production system coding, the effort appears more evenly distributed on the latter stages, because of more fluid development, in contrast to radical changes to the developing software. Even with these improvements, the effort expended up front in developing the prototype is far too excessive for its intended purpose. Considering that all that effort is spent on only a partial representation of the requirements and that the prototype will be thrown away, the efficiency of the methodology from this perspective is not acceptable by today's standards.

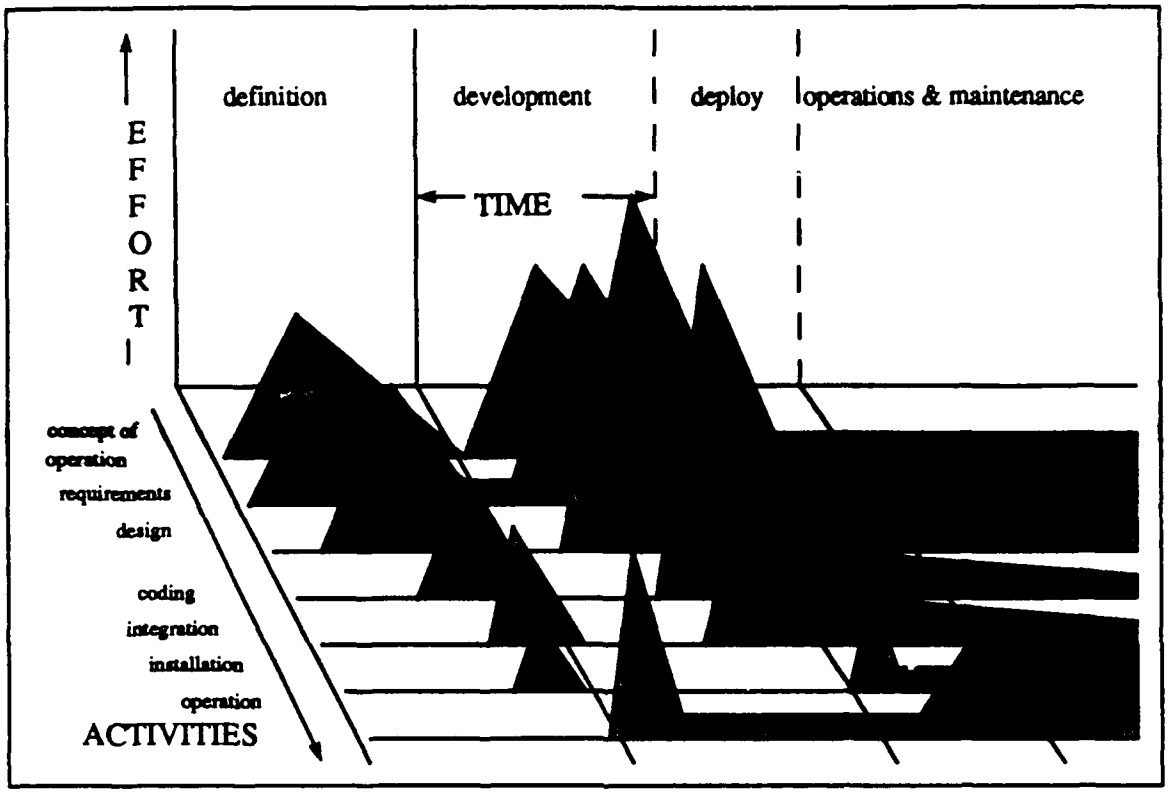


Figure 34. Three-Dimensional View of Rapid Throwaway Methodology

6. Implementation Outlook

The rapid throwaway methodology is achievable now, given the absence of reusable software components. The prototype could be constructed manually, relieving the need for many of the tools in the prototyping center. Obviously, the addition of using reusable software components extends its implementation window out to near-term range, depending on the development of the required tools and research into reusable software components.

Since it is achievable now, the methodology can be viewed as a first-generation methodology. The software industry has two perspectives to consider. The first is to get prototyping "on board". This methodology appears promising. It enters a new generation of software development without deviating greatly from current

development practices. So from this perspective, the hard-line, experienced software developers would be more comfortable with introduction of this methodology. On the other hand, the excessive effort that needs to be expended may turn away some developers that are skeptical of the prototyping paradigm in the first place. It is not logical to accept the extra work required just to get a partial set of requirements validated early. It is primarily the developers that can't see the forest for the trees, that will criticize this methodology and probably will lobby hard for its abolishment. If it is introduced as a first-generation prototyping methodology, the point needs to be made that rapid throwaway is only an initial representation of the new rapid prototyping paradigm and will serve to remedy some of the existing problems associated with the traditional life cycle model.

C. INCREMENTAL DEVELOPMENT METHODOLOGY

1. Prototype Development

The incremental development methodology accomplishes everything that the rapid throwaway methodology does, only in more detail and more efficiently. The incremental process of representing the most difficult requirements first, followed by the simpler ones provides the users with a better perspective of how the system will look upon delivery. Whether it is more efficient to start with the more difficult requirements first, or with the simpler ones, is subject to debate and is primarily dependent on the complexity of the system and the expertise of the developers. It is unlikely that the computer science community will ever agree on this subject, so any effort expended here would be meaningless. But the systematic prototype development

process of starting at one extreme and working towards the other is an enhancement to the rapid throwaway methodology.

The level of detail that the prototype will be able to represent also enhances the requirements validation process. The user is provided the opportunity to see a larger subset of the requirements implemented in the prototype, rather than only a "dirty" set as in the rapid throwaway methodology. The prototype also can provide a better estimation of the production cost, and whether or not real-time constraints will be met. Since the prototype is not evolutionary, the cost of building the prototype in the detail that is provided, should resemble the relative costs associated with coding the production system. The implemented construction also allows the former requirements to be integrated with new or changing requirements in the dynamic development process.

2. Use of Reusable Software Components

This methodology does not specifically include the use of reusable software components. However, just as with the rapid throwaway, this methodology can integrate the reusable software components methodology to make the construction of the prototype and production coding more efficient. Since the prototype is not used as the production code, the process of manually coding both the prototype and the production system is terribly inefficient without the prototyping tools and environment to facilitate the use of reusable software components.

3. Evolutionary Prototype Production

The incremental development methodology does not use the prototype after validation. The effort expended in building both the prototype and production system greatly affects the cost of the software and in meeting the required delivery times.

4. Meeting User Needs

Figure 35 represents the incremental development methodology in comparison with the traditional life cycle model [Ref. 7: p. 6]. The authors note in [Ref. 7: p. 6] that the initial development time is reduced; the initial functionality (A) is less than for the traditional approach (B); and the average slope of the functionality line (A-C) is higher than for the traditional approach (B-D), indicating increased adaptability. The stair-step implies an intention to develop a series of well-defined, discrete, incremental builds of the system.

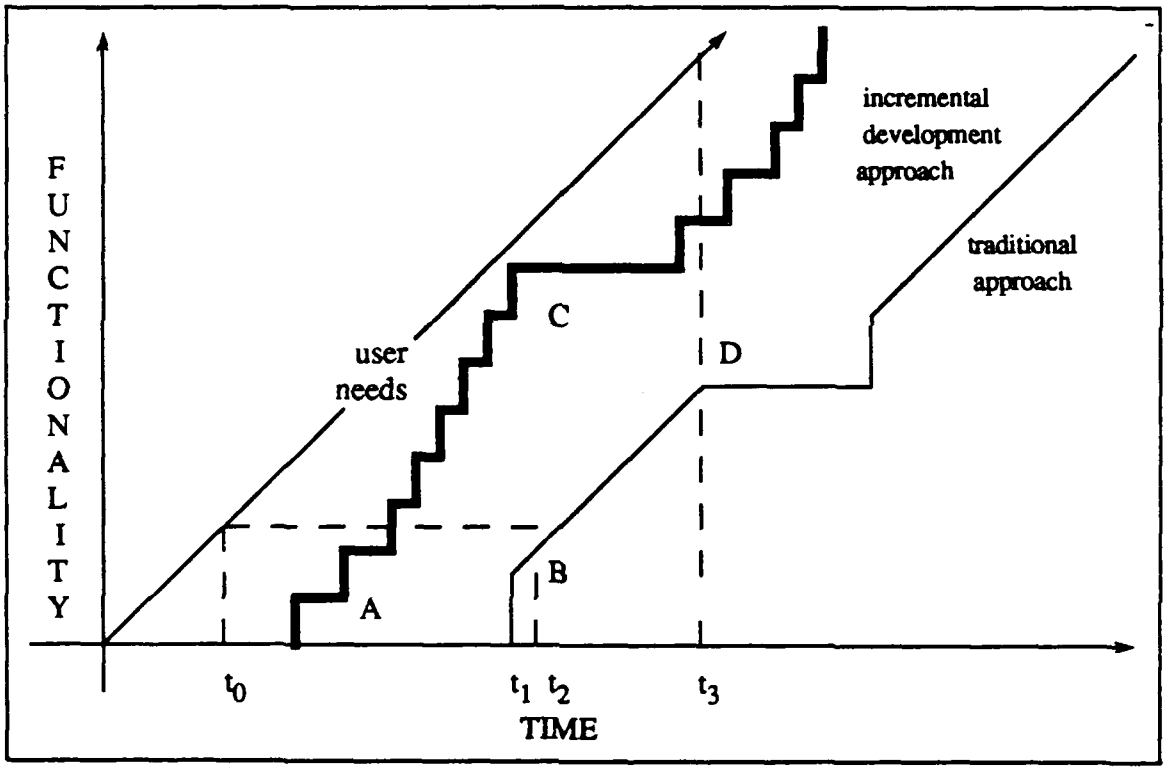


Figure 35. Incremental Development vs. Traditional Approach

The improvements in the area of inappropriateness is reflective of the increased ability to integrate changing requirements or needs and by allowing the users the

opportunity to validate a larger subset of the requirements through the use of the incrementally developed prototypes.

5. Time, Activities, and Effort

Figure 36 provides the three-dimensional view of the incremental development methodology [Ref. 7: p. 6]. The authors point out in [Ref. 7: p. 6] that the effort expended in defining the requirements analysis phase is still substantial, and is comparable to the rapid throwaway methodology. But as the requirements are incrementally developed, the effort is reduced because the more complex requirements are done first. So, the declining peaks of effort are reflective of the more simple (well defined) requirements integrated with the more complex ones. After the more complex requirements are developed, the major effort used is for making the necessary changes

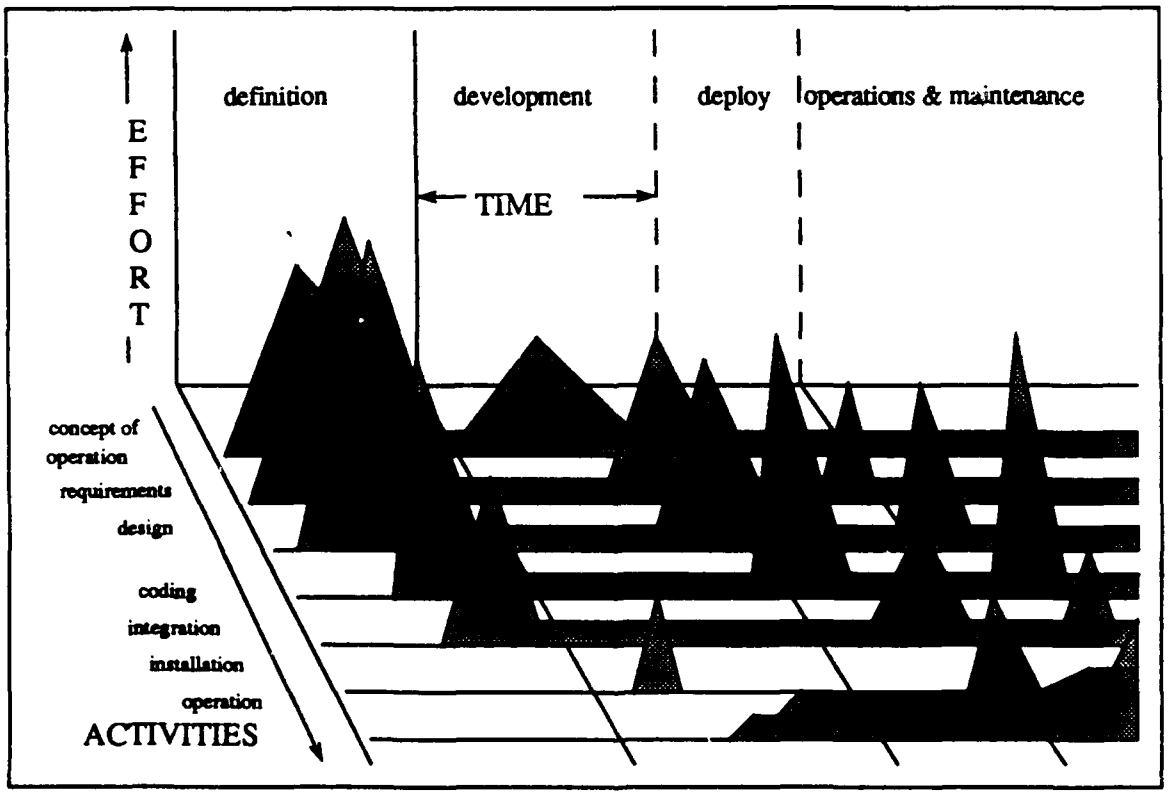


Figure 36. Three-Dimensional View of Incremental Development

or enhancements based on the users validations of the prototypes. Because the complex (not clearly defined) requirements are prototyped up front, there is a significant amount of effort expended in designing the architecture for the entire system. The incremental, but relative consistency of the coding efforts, as well as the installation and operations/maintenance activities, are reflective of the improvements in the requirements validation activity of the requirements engineering process.

Another enhancement that this methodology offers is the ability to validate particular modules of a system and proceed into the next phase (production coding) while the other modules of the system are being prototyped and validated. Not all systems can take advantage of this, given the dynamic nature of the development process, but in some cases it may apply. This enhancement could be very effective, if applicable, in meeting delivery deadlines and thus in satisfying user's needs sooner.

6. Implementation Outlook

The incremental development methodology can be partially implemented now. To fully meet its potential and the goals of the new paradigm, the methodology is most probably a short-term goal. The integration of reusable software components into this methodology is essential if wide acceptance is to be gained The prototyping tools and their associated environment must be built to support this methodology. Once the environment is in place, the incremental methodology can be implemented given current technology.

D. EVOLUTIONARY PROTOTYPING METHODOLOGY

1. Prototype Development

The evolutionary prototyping methodology develops its prototypes in a similar fashion as the incremental development methodology. The prototype is incrementally built, but the simpler requirements are prototyped first, followed by the more complex ones. The same debate holds here as to which technique is more efficient. Intuitively, building upon known (simpler) requirements or strengths seems more logical than tackling the unknown (complex) requirements first. But this is merely intuitive and there are some logical arguments to support the other technique as well.

The most appealing enhancement that this methodology offers is that the prototype serves as the production system. The benefits of not having to build a production system from scratch after the prototype is validated should save on many resources (time, cost, maintenance, delivery rates, etc.). The positive side affect of this is that the users validate the prototype and production system at the same time. The user, in essence, validates the system as it is being developed and there is no chance of replication errors as in the rapid throwaway or incremental development methodologies. The probability of user dissatisfaction should be considerably reduced, and in areas where the dissatisfaction occurs, the user is not surprised and is aware of the problem or shortfall prior to delivery. Does this solve the requirements engineering dilemma? Not necessarily! The software development process is still very dynamic and requirements may change, even after a particular prototype representation has been validated by the user. But this methodology seems to allow for the dynamic conditions, more so than the other two methodologies already surveyed. The process of making enhancements is much more efficient that in the traditional life cycle model.

There are some costs associated with the advantages gained through this methodology. "To use the prototype as the production system will require an intensive prototyping tools environment to support its RAMP (Reliability, Adaptability, Maintainability, and Performance)". [Ref. 7: p. 7] The other cost is time. The time-consuming effort involved in not only constructing the prototype, but simultaneously developing the design architecture for the operational system places the "rapid" intent in jeopardy. That is why the prototyping tools environment is so essential to the implementation of this methodology.

2. Use of Reusable Software Components

The use of reusable software components in this methodology is not specifically noted, but just as in the previously surveyed methodologies, their integration into this methodology appears essential. This is especially important given the complexity of the development process and the enormous time-consuming factors involved. Since the prototype will serve as the production system, the use of reusable software components makes great sense, especially considering the enhancements and maintenance efforts involved. The use of reusable software components will certainly bring the time issue closer to meeting the "rapid" intent of the methodology and the goals of the new paradigm.

3. Evolutionary Prototype Production

The methodology supports the evolutionary process of providing an executable prototype that will serve as the production system. The efficiency of not duplicating efforts in developing software is moving closer to full automation. Although not optimally fulfilling the potential of automation, the manual efforts are considerably reduced and those that still exist in some respects complement the automation process.

4. Meeting User Needs

Figure 37 represents the evolutionary prototyping methodology in comparison to the traditional life cycle model [Ref. 7: p. 7]. The authors note in [Ref. 7: p. 7] that the figure shows the initial prototype emerging early in the development, followed by a period of continuous functional expansion though the exploration of new areas of user needs, while simultaneously refining the previously developed functions. As a result, the solution evolves closer and closer to the users needs. Eventually, it too will have to be redone or undergo major restructuring in order to continue to evolve.

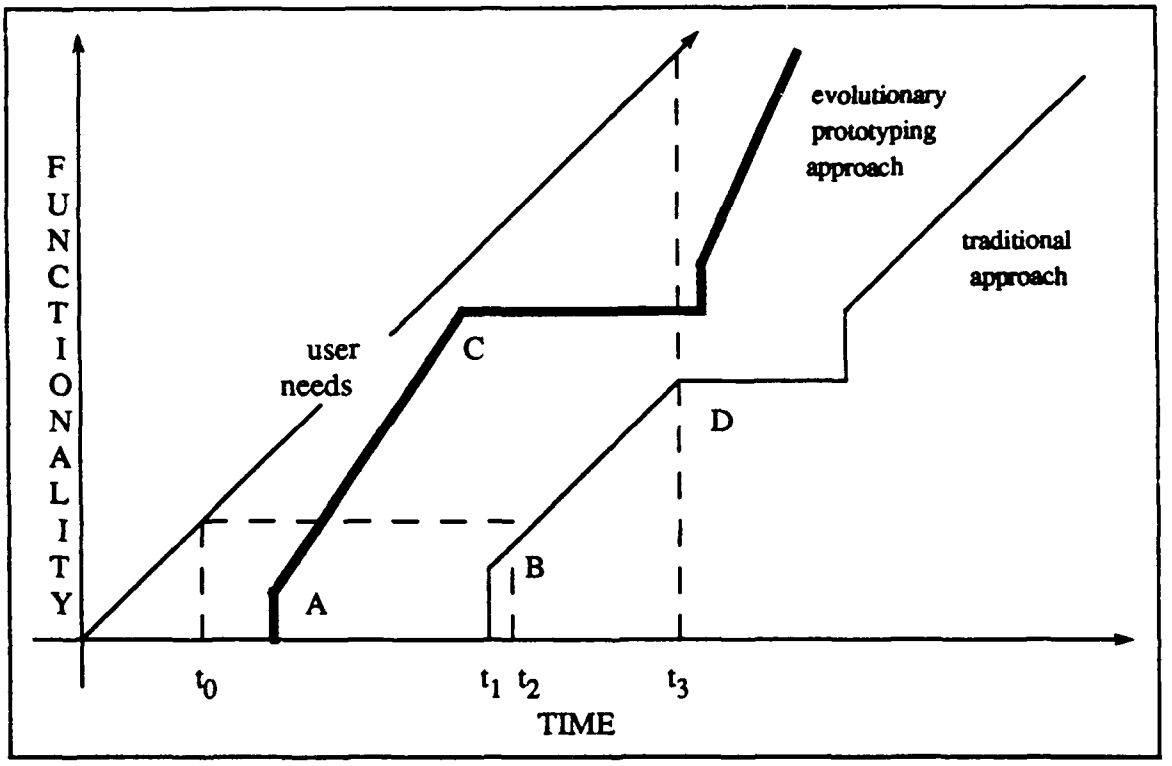


Figure 37. Evolutionary Prototype vs. Traditional Approach

The authors explain in [Ref. 7: p. 7] that as with the incremental development approach, the slope (line A-C) is steeper than the Traditional model (line B-D) because the evolvable prototype is designed to be far more adaptable. Also, the line

A-C in Figure 36 is less stepped than line A-C in Figure 34 because of the replacement of well-defined and well-planned system builds with a continuous influx of new and perhaps experimental functionality.

5. Time, Activities, and Effort

Figure 38 represents the three-dimensional view of the evolutionary prototyping methodology [Ref. 7: p. 7]. The authors claim in [Ref. 7: p. 7] that the initial prototype can be done quickly and the requirements effort minimized, as the best understood parts of the system are being implemented. Thus, the decrease in requirements effort up-front. But notice the increase in effort of the design phase (up-front), due

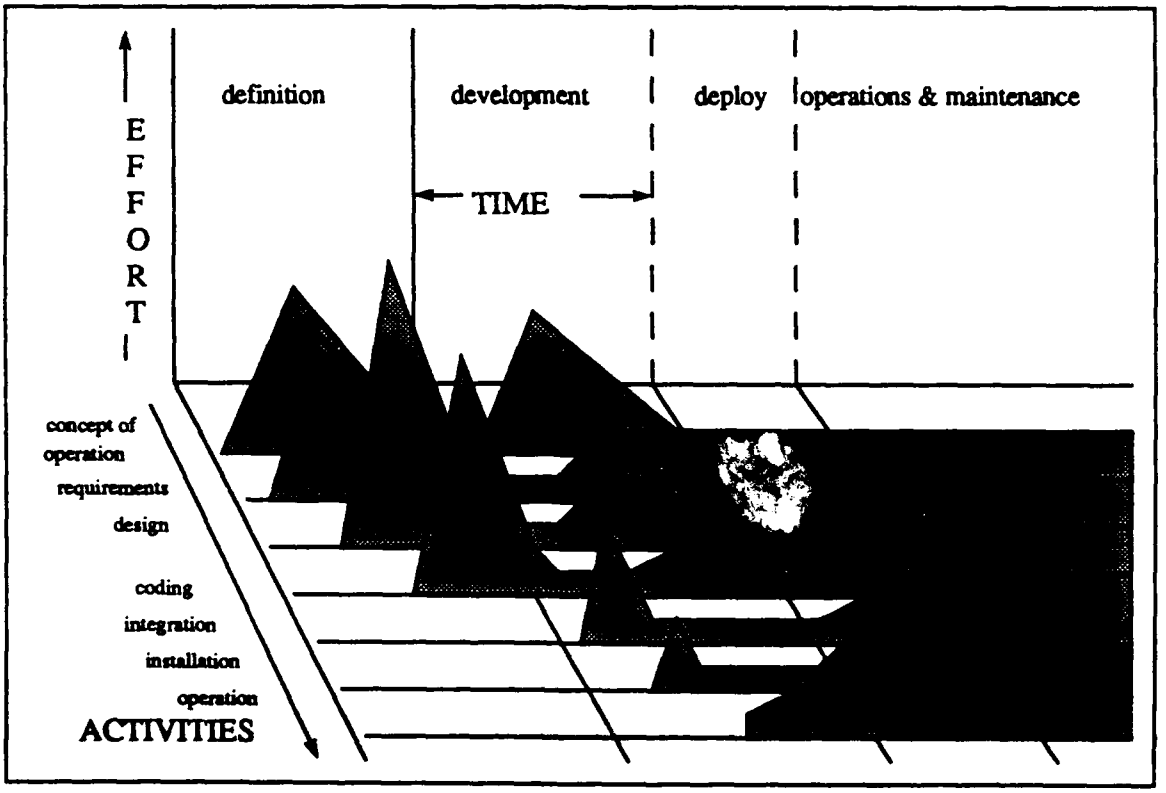


Figure 38. Three Dimensional View of Evolutionary Prototyping Methodology

mainly to the need to architecturally design the operational system. Each succeeding increment is tackling more difficult problems, but only in small pieces; thus the activity levels after the initial prototype are relatively constant and overlap significantly.

The increases in effort in the latter phases of the development, though relatively constant, are worthy of discussion. The extra effort is a result of the enhancements being made on the initial prototype as changes are made. Since the prototype is being designed as the production system and the operational overhead that is entailed to achieve this requires more effort, the overall effort is increased. Also, because the prototype is also operational, the enhancements will be made on larger and more detailed modules. This is in contrast to the partial sets of requirements that the former methodologies provided.

6. Implementation Outlook

The future implementation of this methodology is greatly dependent on the development of the prototyping tools environment. This dependency on the support system will push implementation out beyond the incremental development methodology's implementation. Since the need of more intensive prototyping tools delays implementation, it is more realistically a short-term goal. It is important to note that the delay in implementation does not contribute to apprehensions toward the implementation of the new paradigm by the software industry, rather it is contributes to the void existing in the software prototyping tools environment.

E. REUSABLE SOFTWARE COMPONENTS METHODOLOGY

1. Prototype Development

This methodology is strictly an implementation feature rather than an independent process. The utilization of reusable software components affects the effort of and efficiency with which the prototype is constructed. For this reason, reusable software components should not be viewed as a "stand-alone" methodology, but should be integrated into the other methodologies previously surveyed. The utilization of reusable software components in both development of prototypes and production systems (in rapid throwaway and incremental development methodologies) makes the coding process more efficient and provides a near-term context for introducing a first generation automatic code generating system.

The development of the prototype using reusable software components does not enhance the requirements validation process. The users can equally validate prototypes that are manually coded or coded using reusable software components. But the effort involved from the designer's or developer's perspective is reduced and the prototype can potentially be developed more quickly.

2. Use of Reusable Software Components

The two main issues involved are how software reliability should be improved and debugging effort should be reduced for the parts of the system built from reusable software components. Intuitively, the function of managing the components library and retrieving functions should coincide with current DBMS (Data Base Management Systems) technology. The problem is that current DBMS technology is based on relations and is not compatible with the requirements of reusable software components. Therefore, the need for a prototyping language that is both specification-based

and design-based is necessary to fill the void in current DBMS technology. The development of a new language is both complex and time-consuming. The management of the reusable software components library focuses on organization and storage space. Both of these solutions to the problems are achievable given current and near-term technology, but the tasks of constructing, testing, and organizing the components will not be something that will be completed in the near-term future.

3. Evolutionary Prototype Production

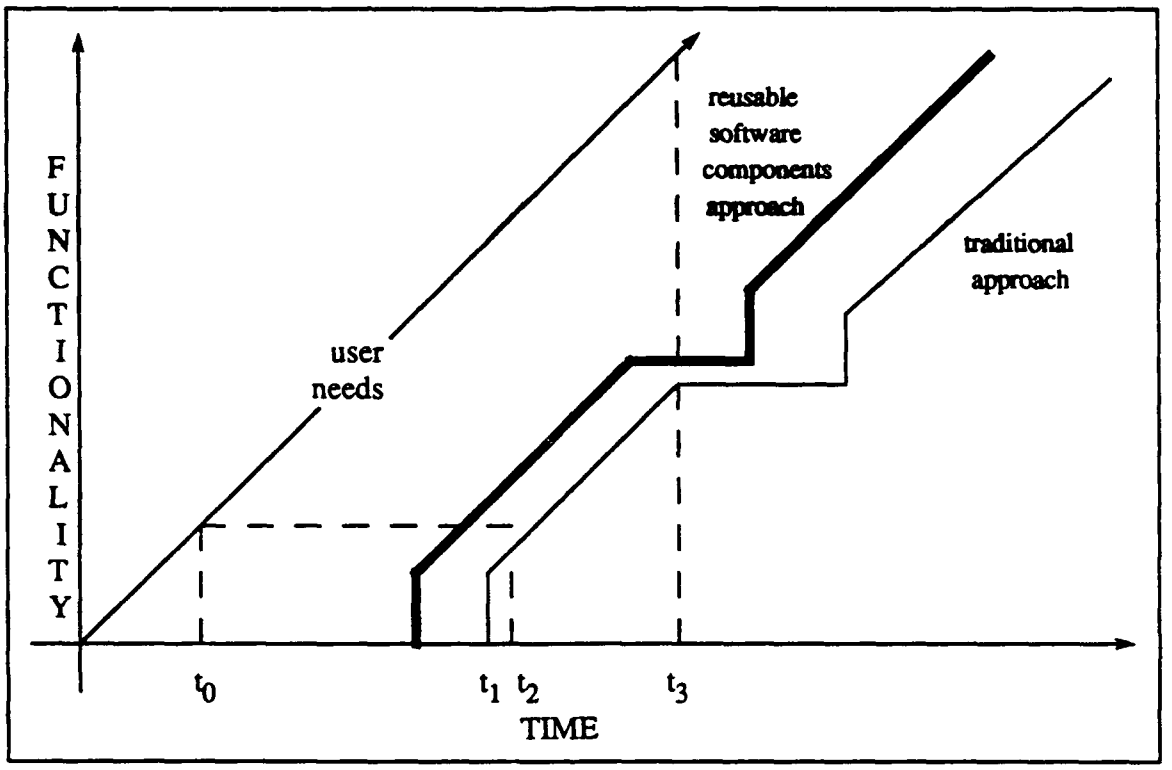
The use of reusable software components can produce executable prototypes that serve as production systems. The major differences are how reusable components are used in the methodologies, the level of detail required in developing the prototype, the architectural design requirements, and the constraints that the components must meet.

4. Meeting User Needs

Figure 39 represents the reusable software components methodology in comparison with the traditional life cycle model [Ref. 7: p. 8]. The authors point out in [Ref. 7: p. 7] that the time required for development is the only parameter which changes, with the amount of software "reused" determining the significance of decrease. There is the potential (not shown) for the slope of the functionality curve (adaptability) to be greater due to the structure and modularity required by the reusable software methodology.

The decrease in development time depends on the complexity of the system and the amount of reusable software components used, and therefore should not be construed to be constant. The reduced development time can be included in each of the previously surveyed methodologies and should bring the development time closer

to meeting the user needs. So the "area of inappropriateness" should be reduced if reusable software components are integrated in each of the other methodologies.



5. Time, Activities, and Effort

Figure 40 represents the three-dimensional view of the reusable software components methodology [Ref. 7: p. 7]. The authors claim in [Ref. 7: p. 7] that the overall impact of reusing software components should be shorter development schedules (less new design and code development and less first-time testing) and more reliable software (by using components that have been previously "shaken down").

The use of reusable software components does not affect the requirements phase, but does affect the design phase, because of the structure provided by the

components specifications. The effort associated with coding is in defining the specification and constraints by which the components will be retrieved and implemented.

6. Implementation Outlook

This methodology is also dependent on the development of a prototyping tools environment. The development of a prototyping language is an additional requirement that is necessary to implement this methodology. Because of the complexity of developing the environment and the complexity of developing a prototyping language to support this methodology, it is realistic to project its implementation as a short-term goal. If reusable software components are integrated in the first two methodologies,

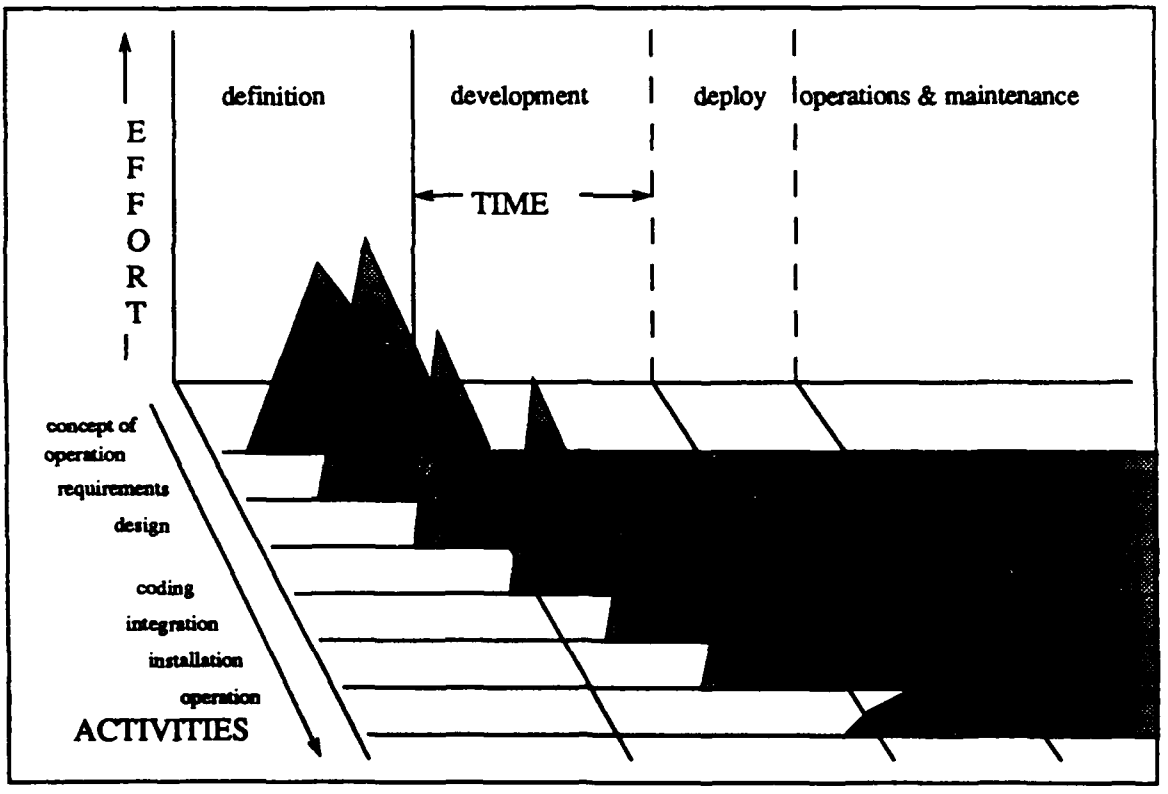


Figure 40. Three-Dimensional View of the Reusable Software Methodology

the implementation time may need to be expanded, but the implementation time for the evolutionary prototyping methodology should not be extended. The effort

involved in developing the independent parts of the environment to support the reusable software components methodology is comparable in terms of complexity.

F. AUTOMATED SOFTWARE SYNTHESIS METHODOLOGY

1. Prototype Development

The development of the prototype under this methodology is based on automatic design, coding, and operational system activities. Theoretically, using a VHLL to automatically generate the prototype and design architecture of the production system is close to the optimal process of software development. Unfortunately, the technology is not currently available to implement this methodology and is not expected to be available any time soon.

2. Use of Reusable Software Components

This methodology uses the reusable component concept to an extent, but relies more heavily on the VHLL to generate the code and design architecture. The components of this methodology will be more skeletal in terms of actual program coding. More advanced research is required to define the process of how the prototypes will be coded.

3. Evolutionary Prototype Production

The prototype produced by this methodology will not only be executable, but will also drastically reduce the requirements validation process because of the automated synthesis and therefore meet the user's needs more closely than in the previously surveyed methodologies. The production system would also be more maintainable, because of the automated synthesis and its ability to make enhancements with very little effort involved.

4. Meeting User Needs

Figure 41 represents the automated software synthesis methodology in comparison with the traditional life cycle model [Ref. 7: p. 8]. The authors point out in [Ref. 7: p. 8] that the reduction in development time and cost is significant as depicted by the slope (line A-C). The reductions are so dramatic and the overall efficiency improved so much that adapting "old systems" would rarely be more cost-effective than re-synthesizing the entire system. The longevity of any version would therefore be low, as is depicted in the stair-step representation of the figure. The horizontal segments represent the time the system is utilized and the time needed to upgrade requirements. The vertical segments represent the additional functionality offered by each

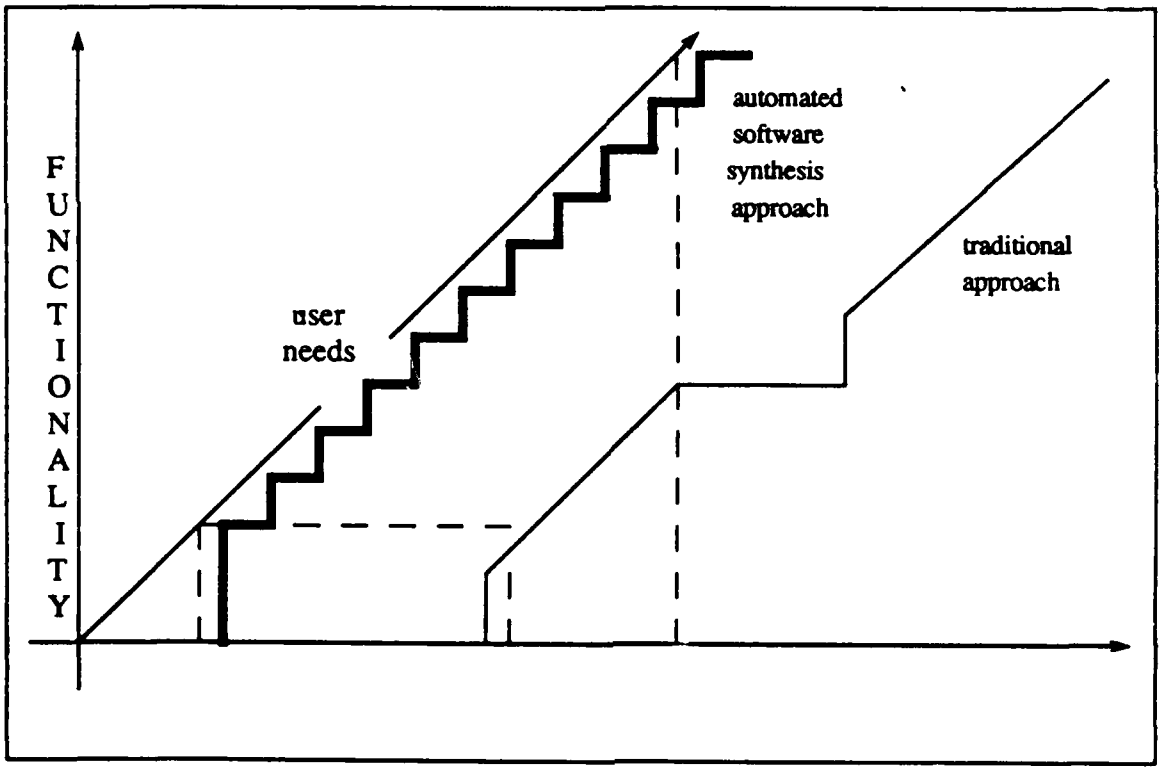


Figure 41. Automated Software Synthesis vs. Traditional Approach

new generation. The decrease in the area of inappropriateness and shortfall are significant and very nearly meet the "instant gratification" level of meeting user's needs.

5. Time, Activities, and Effort

Figure 42 represents the three-dimensional view of the automated software synthesis methodology [Ref. 7: p. 8]. The requirements effort still exists, but once the requirements are defined, the enhancements require little effort as compared to the previously surveyed methodologies. The VHLL will absorb the effort associated with the design, coding, and integration activities. The significant decrease in effort is contributable to the synthesizing and automatic code generation features that the methodology offers. The ability to fully automate the software development process

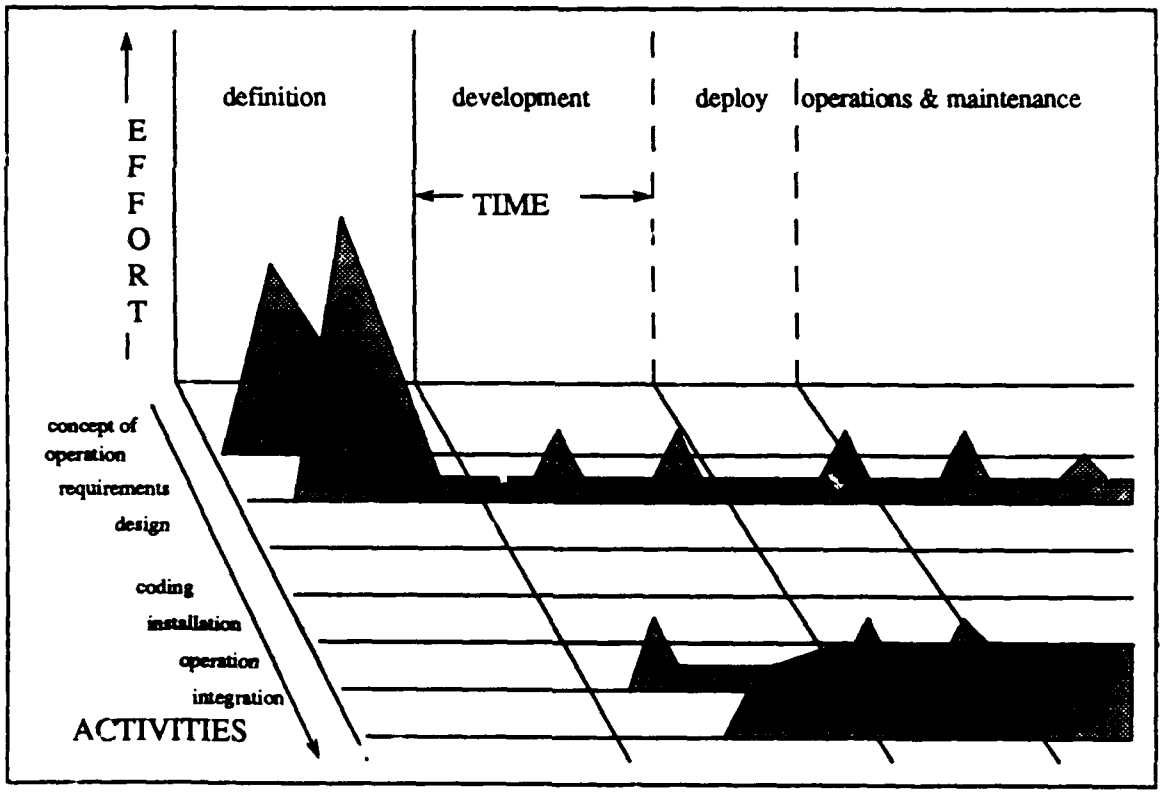


Figure 42. Three-Dimensional View of Automated Software Synthesis

will enable every user to get exactly what they want and more importantly when they want it (in almost real-time).

6. Implementation Outlook

This methodology is at least a few rapid prototyping generations away. Neither the hardware or the software technology are currently available to support its implementation. The research of this methodology is still in the infancy stages and needs further development. This methodology should definitely be viewed as a long-term goal. This is not to say that it will not eventually be implemented, but more extensive research must preclude any realistic attempt at implementation.

IV. EVALUATION OF PROPOSED RAPID PROTOTYPING MODELS

The evaluation of the published rapid prototyping models is focused more on the tactical implementation level rather than the strategic approach taken with the methodologies. The models are designed based on either one or a combination of two or more of the surveyed methodologies. The evaluation of the models may be viewed as an extension of the strategic evaluation information of the methodology or sets of methodologies from which the models are designed. In some cases a particular model that integrates two or more complementary methodologies may avoid problems that are caused by one of the methodologies. If this is the case, the features or interaction of the features that provides the compensation are noted.

The evaluation criteria for the models will be focused on the internal design features of each model, the development of the prototype, the support system environment, and the fulfillment of the tactical goals of the proposed paradigm. The evaluation criteria are *1) formal and explicit to enable automated consistency and completeness checking, 2) prototype development, 3) measurability in terms of cost estimation, planning, and completeness, 3) use of reusable software components, 4) maintainability, 5) documentation coding produced, 6) real-time systems, 7) user interface capabilities, and 8) performance issues.* Some of the evaluation criteria for the models could not to be evaluated due to the absence of detailed descriptions. In cases where some vagueness exists, the appropriateness of further research required or potential implementation shortfalls are noted.

A. EVALUATION CRITERIA DESCRIPTIONS

Formal and explicit to enable automated consistency and completeness checking: This criterion addresses the ability to achieve and demonstrate consistency and completeness in the specification and design levels in modeling the prototype and the production system. Dr. Berzins declares in [Ref. 26: p. 51] that some aspects of the completeness and consistency of requirements can be checked automatically. Examples of constraints that can be automatically checked are definition completeness and type consistency. Type consistency means that the types of the objects involved in each concept agree with the definition and each use of the concept. Other kinds of automated checks are also possible, many of which are more difficult to implement. Requirements tracing, control constraints, syntax, and objects are all areas that can be checked automatically for consistency and completeness. These four areas will be the focus of the evaluation.

Prototype development : This criterion addresses how efficiently the prototype is developed. The evaluation of this criteria, with respect to the models, will focus more on the actual construction of the prototype rather than on the theoretical or conceptual representation covered in the evaluation of the methodologies.

Measurability in terms of cost estimation, planning, and completeness : The development of the prototype should enable a close estimation of cost of developing the production system for budgeting considerations. The prototype should entail the level of planning required to produce the production system. The prototype should give a reasonable representation of completeness in terms of requirements implementation and real-time effectiveness.

Use of reusable software components : This criterion addresses how the reusable software components are retrieved, used, and the complexity and efficiency involved.

Maintainability : This criterion addresses how well the model allows for evolutionary changes and whether or not the maintenance effort is improved by the design and implementation of the model.

Documentation coding produced : This criterion addresses whether documentation is automatically or manually produced to supplement the coding. This documentation of concern is primarily that produced when reusable software components are linked. However, it is also important to consider the quality of the documentation for the entire development process.

Real-time systems : This criterion addresses whether the model handles real-time constraints or does it leave the real-time issues to the underlying system.

User interface capabilities : This criterion addresses whether the model permits the use of the user interface features currently available or software developed without the aid of any tools. It also addresses whether graphics features are included to facilitate dataflow or documentation requirements as the software is being developed.

Performance issues : This criterion addresses how well the model performs in producing large real-time systems, both conceptually and realistically (if currently being implemented). This criterion also addresses real-time effects, prototype development time, enhancements, and meeting delivery schedules.

B. CAPS (COMPUTER AIDED PROTOTYPING SYSTEM) RAPID PROTOTYPING MODEL

1. Formal and Explicit to Enable Automated Consistency and Completeness Checking

CAPS has only limited automated consistency and completeness checking. The only automated process for checking for consistency is facilitated by the syntax-directed editor. The syntax-directed editor, a component tool of the designer interface, helps speed up the reusable software component retrieval and linking processes by eliminating syntax errors, automatically supplying keywords, and prompting the designer with a choice of legal syntactic alternatives at each point [Ref. 8: p. 26]. The syntax-directed editor, in support of PSDL, handles all the context information errors. The process of correcting syntactical errors is not fully automated and requires some interaction between the system and designer to resolve errors. So the automation of this process is consistent with meeting real-time constraints, but is limited to only the context information errors.

The model does not provide any automated requirements tracing for consistency or completeness. This is also attributable to the inability to perform automatic theorem proving. The task of checking for completeness and consistency is left solely to the designer. The manual process of requirements tracing is enhanced by the development of the process, but still is subject to errors or oversights in the requirements engineering process.

The model does address consistency and completeness checking, as much as current technology allows. The ability to check for context-free inconsistencies and errors can be integrated into the model either during model development, if the

technology becomes more advanced, or as a future feature after the model is initially implemented.

2. Prototype Development

The CAPS prototype is developed incrementally and is intended to be evolutionary. The design-based PSDL language is used to retrieve, provide instantiation with regard to control constraints, and link reusable software components. The linking of the components results in an executable prototype that represents the user and system requirements.

The use of reusable software components is an efficient means of producing the code for the prototype. Conceptually, the process of retrieving the components is efficient and will result in rapid development of the prototype. The efficiency of the prototype development is based on two important factors. The first is on the ability of the designer to decompose the specifications to match the components in the software library. The quality of the decomposition of the specification will affect the development of the prototype. Designers experienced in the prototyping process will eventually provide specific specifications, but the initial systems will probably suffer from the attempts of novices. The other factor is the completeness of the software library. The effort and time expended on manually coding components that are not in the software base will also affect the development process. This problem will also improve as the learning curve of designers improves.

3. Measurability in Terms of Cost Estimation, Planning, and Completeness

Because the model is evolutionary, the cost of developing the prototype closely reflects the total cost of the production system. Even though there may be some cases where the prototype developed by retrieving reusable software components will

requires manual enhancing to meet production system needs, the costs will still be close. This is important in terms of defining the upper bounds of what requirements can actually be implemented given the users resource constraints.

The planning effort to develop the prototype approximates the total planning effort of the production system. . Once the prototype is validated by the users, little-additional planning will be required to transform the prototype into the production system.

The measurability of completeness is relatively guaranteed by the evolutionary design of the prototype. Completeness cannot be absolutely guarenteed because there will be cases where the validated prototype needs detailed enhancements to satisfy the production system requirements. Even so, the level of completeness that the designer can represent to the user through the prototype is very important in terms of validation.

4. Use of Reusable Software Components

Since CAPS is evolutionary, the reusable software components in the prototype also serve as the coding for the production system. The process of retrieving the components only once is more efficient than having to retrieve components for the prototype and then again for the production system.

The development of the component software base is very complex and is conceptually designed to be object-oriented. The structure of the software base is not completely described and is still being researched. Given the recent success of object-oriented software products, the structure of the software base should be defined more clearly in the near-term future.

5. Maintainability

CAPS has some maintenance features that improve upon current software development procedures. The evolutionary changes in the maintenance phase are more rapidly constructed because of the use of reusable software components and the prototype development process. But the CAPS model does not handle the maintenance effort automatically. If enhancements need to be made to a component, any interfacing between linked components and the changed component is unaffected by the change. The components need to be re-linked to support the changes. If major maintenance changes are required, then the prototyping process may need to be re-initiated. This is obviously not an optimal solution to the maintenance problem, but is reflective of the current technology.

6. Documentation Coding Produced

CAPS requires a specification part for each component and the PSDL implementation part for the composite components documents the linking process between components. Also, the paraphraser component provides English explanations. Maintenance is done at the PSDL level. The maintenance phase does not have to "look" at automatically produced code, so documentation is irrelevant.

7. Real-Time Systems

CAPS provides special features particularly appropriate for real-time systems. PSDL and the execution support system provide these features.

Dr. Luqi explains in [Ref. 8: p.27] that the PSDL executable prototype is used to check real-time requirements because the critical timing constraints and the most important concerns, e.g. maximum execution time, minimum response time, and synchronization are very hard to validate without actually constructing a valid schedule

and observing the execution of the prototype. Most real-time systems are used to monitor and control physical processes external to the computer in the embedded system. The precision and accuracy requirements in the design of a real-time control system complicate the demands on the execution of the designed software system. For these reasons, the design of real-time systems imposes a different set of demands. The formal structure in PSDL specifying real-time constraints provides a basis for automating the production of code from the formal requirements specifications to the underlying programming language. The execution of PSDL prototypes helps to verify that the design of an embedded system with given timing constraints for the components in the prototype will interact with its environment in a way that meets the timing constraints of the system as a whole.

By accentuating the real-time constraints in the design process, the task of insuring that the prototype reflects the constraints must be handled by the tools within the prototyping system. These tools are components of the execution support system. They are the *static scheduler* and the *dynamic scheduler*. Dr. Luqi points out in [Ref. 8: p. 1] that the purpose of the static scheduler is to schedule times for the computations with hard real-time constraints in such a way that all the timing constraints will be guaranteed to be met. Time slots are statically allocated for the worst-case execution times of the operators. The abstract treatment of the timing information is an important property of the data flow since only the essential time ordering affecting the events in the computation are given. These time orderings act as constraints on the static scheduler, and allow the flexible exploration of schedules for multi-processor configurations. The purpose of the dynamic scheduler is to utilize time slots not

needed for the time critical computations to schedule the computations that do not have hard real-time constraints.

Portions of PSDL, the static scheduler and the dynamic scheduler have been implemented [Ref. 27]. These tools are theoretically sound, but full implementation of the tools may expose some unforeseen problems.

8. User Interface Capabilities

CAPS features some user interface features that will facilitate the prototype development. Dr. Luqi claims in [Ref. 8: p. 27] that the graphics tool, which is part of the syntax-directed editor, provides a graphical view of the dataflow diagram part of the PSDL implementation of a component module. The graphics tool helps the designer visualize the relationships between the components of a decomposition by means of a two-dimensional dataflow diagram, and provides a convenient way to enter and update the decomposition information in the enhanced dataflow diagram, which is part of a PSDL implementation of a component.

This graphical representation of dataflow will make it easier for designers to evaluate the effect of the prototype development. It is much easier to visualize and understand a graphical representation than to interpret hard text descriptions of the same process.

9. Performance Issues

CAPS has some significant performance features. Conceptually, given current technology, it provides the tools and design to produce a prototype that is executable and evolutionary. Once the model is implemented and designers become experienced with PSDL and the development process, the performance resulting from this model will be much greater than current methods of software development. Although there

is considerable automation in this model, there remains a significant human interaction effort. This increase in automation may be integrated into the initial implementation as technology and research efforts allow.

The performance feature that is most attractive is the ability to handle real-time constraints. The handling of real-time constraints allows the prototype and production system software to execute in a hard real-time environment. The added automation discussed earlier only enhances the development process and not necessarily the execution of the software.

C. IPS (INTEGRATED PROTOTYPING SYSTEM) SOFTWARE PROCESS MODEL

1. Formal and Explicit to Enable Automated Consistency and Completeness Checking

The IPS Software Process Model [Ref. 20] also provides for only limited consistency and completeness checking. The model features a syntax-directed editor which corrects only context information. Errors in context-free information are left to manual means, just as in CAPS.

The only other consistency and completeness checking that is performed is done through an interactive process between the user, designer, and the DAA (Design Activity Agent) [Ref. 20]. The graphical representations are produced by the internal tools within DAA. DAA provides the graphical representation of the hierarchical design of the system and then the designer and users review the structure of the designed system. The errors or misrepresentations have to be manually detected and changed because ART (Automated Reasoning Tool) [Ref. 20] is not designed to check for context-free defects.

2. Prototype Development

There are two different prototypes produced in the IPS Software Process Model. The design prototype is developed within the DAA environment. The design prototype is the focal point of the model and is intended to be the prototype that will satisfy a majority of the validation requirements. The other prototype is an executable prototype that is transformed from the design level code into high level programming code by an automatic program generator.

The design prototype is constructed efficiently, using reusable DODAN components from the ART knowledge base. The hierarchical structure of the design components after linking is easy to represent graphically and thus easier to review in the validation process. Since the design components are much smaller in comparison to programming language coded components, and have a hierarchical structure, enhancements or modifications to the design structure are easier to execute.

The development of the executable prototype is not clearly defined. The executable prototype will somehow be developed by transforming the design level code into a high level programming language. Whether the prototype will be constructed of reusable software components or not is undefined at this point. But the use of a reusable design component implies that reusable software components will be used in some manner.

3. Measurability in Terms of Cost Estimation, Planning, and Completeness

The IPS model, as currently defined, only provides limited cost estimation of the overall production system. Since the development process of the executable prototype is not clearly defined, it is unclear what the relationship is between the cost of

developing the design prototype, the cost of developing the executable prototype, and the cost of the overall production system.

The planning effort expended in the design phase should account for the measurability of planning for the remaining efforts in the development of the production system. This is the intent of the model. If sufficient planning efforts are expended in the requirements, specifications, and design phases, then the automatic program generator should be able to transform those coded efforts into high level programming language code. This claim is conceptually valid, but only if the automatic code generator is fully automated.

The completeness of the production system should also be primarily absorbed in the first three stages. The optimal design prototype, along with the automatic program generator should conceptually secure completeness. This is dependent partially on the automatic program generator, but probably more on the ability of designers and users to insure completeness in the design phase.

4. Use of Reusable Software Components

Yin and Tanik describe in [Ref. 25: p. 3] that the use of DODAN components from the ART knowledge base implies the intended use of reusable software components in the development of the prototype, and therefore in the production system. The structure of the ART knowledge base, which contains the design components, is object-oriented. The schema in the knowledge base represents an object or class of objects, its associated attributes, and its membership in other classes . The structure of this knowledge base supports modularity. This modularity should facilitate the retrieval process.

The design of a software component base for the high level language is not defined, but the same basic conceptual design as the ART knowledge base seems logical. The additional features such as inheritance relations and interfacing rules should be included in the reusable software base to facilitate maintenance as well as consistency and completeness checking efforts.

5. Maintainability

Conceptually, one of the most attractive features of the model is its ability to handle maintenance very efficiently. If modifications or enhancements are necessary, then the designer need only go back to the design phase, make the modifications, and then let the automatic program generator complete the coding efforts. Since the designer never has to go into the system produced coding, the maintenance effort is significantly reduced. The ART knowledge base management system effectively supports the maintenance process in the design phase of the development.

6. Documentation Coding Produced

The IPS Software Process Model does not produce any additional documentation other than that which is included in the components in the knowledge base. This would pose a problem if maintenance was dependent on modifying system-produced coding. But the maintenance effort does not require this dependency and the authors of the model contend that the automatic program generator will never require interpretation of the system-produced code. If this authors' contention is correct, then the lack of documentation will not pose a problem. But if the authors' contention is not correct, then the lack of documentation could be disastrous in terms of efficiency.

7. Real-Time Systems

Yin and Tanik explain in [Ref. 25: p. 11] that the IPS Software Process Model, as currently defined, does not insure that real-time constraints are met. The control and timing constraints are not addressed, but may be included in the post-design phase descriptions. The timed event-flow feature depicted in Figure 20 does not handle timing constraints as the name implies. It is used merely to generate the system state transition diagram .

The lack of attention to real-time constraints is a significant oversight. This hinders the model's ability to be recognized as a viable software development model, given the user's growing requirements and software applications.

8. User Interface Capabilities

The conceptually-defined user interface features of DAA are currently dependent on ART. Since the model is dependent on the existing user interface features of ART, it also inherits the existing limitations. As an example, the authors in [Ref. 20: p. 8] note that the ART graphics networks are implemented by using inheritance relations, and has the tree-like structure with one root node. This feature limits the capability of DAA dependency analysis, since a software design may have a data-flow or control flow with a non-tree structure.

Although the existing user interface features are not optimal, they are sufficient to introduce the initial implementation of the model. The conceptual description of the designed user interface features is explicit and well defined. But the implementation of the designed user interface is critical to fulfill the goals of the model.

9. Performance Issues

The evaluation of performance in this model is hampered by its partial design description. The conceptual design of the model up to the design phase is comparable with other models, but the post-design phase description is so vague and strategically presented that performance of the production system cannot realistically be evaluated. It is the strategic description that not only raises questions about performance, but also about the probability of realistically implementing this model in the near to short-term future.

The emphasis on the design phase should enhance the software development process. Since automatic code generation is one of the goals of the new paradigm, the effort has to be expended to validate the design level interpretation of the requirements specification. The research effort that has produced DAA and the design level process description is commendable. If the remainder of the model can be defined and implemented to the detailed level of DAA, then the IPS model could gain wide acceptance within the computer science community.

D. GENERIC (SYSTEMS DEVELOPMENT AND MAINTENANCE ENVIRONMENT) MODEL

1. Formal and Explicit to Enable Automated Consistency and Completeness Checking

The Generic (SDME) Model [Ref. 21] is not defined in enough detail to determine if it performs automated consistency and completeness checking.

2. Prototype Development

The Generic (SDME) Model is designed under the rapid throwaway methodology. The prototype developed under this model is used primarily to facilitate requirements validation. The model then calls for the production system to be constructed in a step-wise refinement similar to the traditional life cycle model. The reasoning behind this effort is that a production system that is constructed with the prototype as the skeleton for the software is too general. The specifics that can be produced by the traditional life cycle model are intended to be preserved by using the Generic (SDME) Model.

The model lacks a specific description of how the prototype is to be constructed. The use of reusable software components is not mentioned. It is implied that the prototype will be constructed rapidly and will only represent a reduced set of requirements deemed most important by the users and designers. Therefore, the implied use of reusable software components may provide more detail than that intended in the model.

The intent for the construction of the prototype is clearly described, but the reasoning is not valid. The generalization concerns described in Chapter II are a reflection of the skepticism of the new paradigm. Granted that the use of the same reusable software components will result in generalization to a certain extent, the designer is free to provide any control constraints or detailed enhancements as required. The prototype is not required, given the user and system requirements, to produce all the specific details of the production system necessarily. They only have to represent the most important requirements. The prototype could be as specific as the designer

wants, although the speed of the prototype development and the intent of the paradigm could be compromised.

The partial set of requirements represents only the periphery of the intended system. The validation process assists in identifying some of the misinterpretations or undefined requirements, but will not represent the interfacing between the prototypes of the requirements. The validated requirements then must be regenerated, a process which is susceptible to misrepresentation or changes to the previously validated requirements. This duplication of effort is not very efficient and does not address the problem of the dynamic state of software development. The cited shortfalls of this model prevent the model from making a great impact on the software development process. The increased effort of developing the prototype does not offset the production benefits in the overall system.

3. Measurability in Terms of Cost Estimation, Planning, and Completeness

The cost associated with developing the prototype in the Generic (SDME) Model does not reflect an estimation of the costs of the overall system. The partial representation of requirements in the prototype and the duplication of effort to develop the production system is so diverse that even increasing the cost by a constant factor would be unreliable.

The planning effort of developing the prototype is also not reflective of the planning effort of the overall system. The planning effort of the prototyping phase is focused on defining the requirements and representing them in the prototype. The issue of design architecture is not addressed until the requirements are validated in the prototyping phase. The planning involved in designing the production system is

dependent on the requirements and the underlying system, and cannot be estimated based on the planning done in the prototyping phase.

The completeness of the prototype is dependent on the needs of the users and the complexity of the proposed system. The definition of the model reflects the inability, in the author's eyes, to produce completeness in the prototyping phase. Therefore, it is not feasible to expect that the prototype developed under this model will provide any reliable estimation of the completeness of the overall production system.

4. Use of Reusable Software Components

The Generic (SDME) Model is not defined in enough detail to determine if the use of reusable software components is intended in the development of the prototype. The model certainly could benefit from the integration of reusable software components, primarily to reduce the amount of time in developing the prototype. The amount of detail provided may be more than required, but the rapid production of the prototype by using reusable software components would outweigh the detail issue.

5. Maintainability

The Generic (SDME) Model, as currently described, will not support maintenance well. The model will suffer from the same problems and shortfalls that exist in the traditional life cycle model. The maintenance or evolution of the system following implementation will require reverting to the internal stages of the model and starting over each time maintenance is required. This is very inefficient and contradicts the intent of the new paradigm.

6. Documentation Coding Produced

Documentation coding produced in the Generic (SDME) Model is totally manual and is dependent on the programmer for the amount of detailed documentation produced. There is no clear definition of any documentation efforts involved in the prototype development process described in the model.

7. Real-Time Systems

The Generic (SDME) Model is not defined in enough detail to determine if the prototype or production system will function as a real-time system. It is doubtful that it will, as currently defined, due to the lack of a prototyping language or tools to support real-time constraints. Any efforts to insure real-time constraints will have to be absorbed into existing programming languages and operating systems.

8. User Interface Capabilities

The Generic (SDME) Model does not define any tools that would provide user interface features that would support the prototyping process.

9. Performance Issues

The prototype development process or construction of the production system in the Generic (SDME) Model will not produce any performance increases. The lack of support system tools and automated processes prevent this model from producing better systems. The only enhancement would be that a subset of the requirements would be validated earlier in the software development process by using the rapid throwaway prototype. But this effort only enhances the software development process and does not address the software performance issue at all.

V. THE NEW PARADIGM'S RELATION TO DoD SOFTWARE ENGINEERING REQUIREMENTS

DoD has long been a dominant agency affecting the development of software engineering. The research funded by DoD has contributed greatly to the current state of current computer technology. The rapid prototyping paradigm is also being supported by DoD, primarily through research funding and the sponsorship of conferences and workshops.

There are many issues that are related to DoD's involvement in supporting the introduction of the new rapid prototyping paradigm. This chapter will address some of these issues, such as DoD's commitment to Ada as its standard programming language and how the current policies and regulations are to be modified to complement the new paradigm. Also, recommendations on overall strategic goals and decomposed near-term, short-term, and long-term goals are provided to facilitate DoD's implementation of the new paradigm to support future software needs and requirements.

A. COMMITMENT TO ADA AS DoD'S STANDARD PROGRAMMING LANGUAGE

DoD's strong commitment to Ada has produced some significant issues in the software industry. One of the issues is that DoD introduced Ada and placed the constraint on software contractors that all new software projects designed for DoD be coded in Ada programming language. This constraint, though not warmly received by

the software industry, has been a factor in the standardization of software products in use by DoD. This standardization has reduced the requirement to support many different programming languages and the required underlying systems to support them. The fact that all new software must be written in Ada has placed some more constraints on how the software is developed mechanically, but the effects on the traditional life cycle model has been minimal.

When DoD placed the constraint of having all software implemented in Ada code, the software industry initially balked. The financial impact of developing software by the industry was only minimally changed, but the financial impact of the maintenance efforts were greatly affected. The reduction in DoD costs of supporting multiple underlying systems to support the myriad of programming languages also affected the software industry. DoD has a growing need for large real-time systems to support its technologically advanced weapons systems and world wide communications requirements. There is no single agency in the nation that has the software needs and financial support to compete with DoD as a software consumer. Therefore, when the software industry was required to produce all code in Ada, they complied to secure and maintain the relationship with DoD. If the software industry in the United States would have refused to abide by this constraint, and DoD went outside of the United States to fulfill its software requirements, the industry would have suffered financially. This influence over the software industry has proven beneficial to not only DoD, but the software engineering field as well.

If DoD exercises the same influence and requires that the rapid prototyping paradigm be instituted as a replacement to the traditional life cycle model, it is reasonable to assume, based on the Ada experience, that the software industry would adopt the

rapid prototyping paradigm. Considering the decreasing defense budget and the increasing software costs, it is important that DoD adopt the paradigm and influence the course of the software industry.

The other significant issue that DoD's commitment to Ada provides is the efficiency gained by the embedded language. The use of pre-designed packages can be viewed as a precursor to the use of reusable software components in the new paradigm. The instantiation efforts and linking efforts are conceptually similar. This similarity and the successes experienced provide the necessary foundation to support an aggressive effort by the software industry to implement the new paradigm. Although Ada cannot be used in its current state as a prototyping language, the developmental lessons learned in the process of introducing Ada should ease the process of constructing a prototyping language to support future implementation.

B. CHANGING TECHNOLOGY REQUIRES POLICY UPDATES

Traditionally, with respect to software, DoD has not had a very good record of changing policies and procedures to keep up with advancing technology. Even the implementation of Ada took a significant amount of time. The process of implementing the traditional life cycle model is a good example of how complicated and lengthy the policy changing process is.

The Waterfall model was introduced in 1970, but was not established as the DoD standard until 1983. While DoD was testing and evaluating the use of the Waterfall Model during this period, development of software in general continued to be in a state of disaster. Even though DoD knew that they needed a software development model, the bureaucratic requirements of exhaustive testing and evaluation prolonged

the implementation of a software development model. Additionally it took a long time for the regulations to be written, approved, and distributed as policy. The foregoing suggests that testing, evaluation, and changing policy on the part of DoD could significantly delay the acceptance of the rapid prototyping paradigm. Figure 43 shows the implementation time-line for the rapid prototyping paradigm, given the same time-line experienced in the implementation of the Waterfall model as the DoD standard.

An additional factor to consider is the additional requirement of developing the automated prototyping support system environment to support this paradigm. Unfortunately, without DoD's expeditious exertion of influence, the development of the tools will continue to plod along. This delay will push back the estimated implementation period. With the reductions in budgetary allocations for software procurement, the excessive delay in affecting policy changes will place many of DoD's software requirements in jeopardy of elimination.

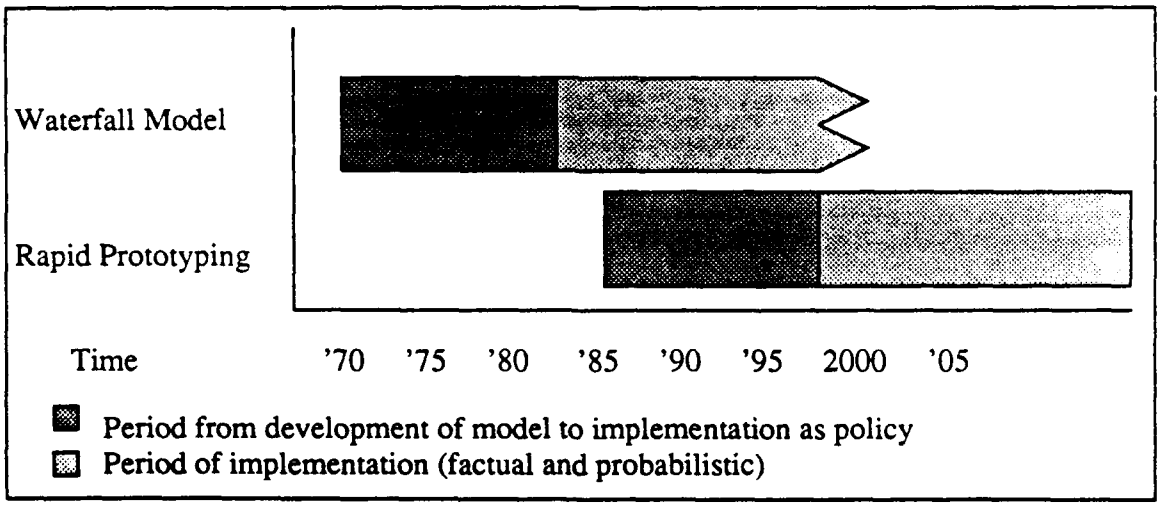


Figure 43. Comparison of Development and Implementation Time-lines

As explained in earlier chapters, the technology is presently available to implement an initial generation of the rapid prototyping . With the rapid advancements in

technology, future generations could be implemented before the implementation estimate depicted in Figure 45. But to take advantage of the full range of benefits of the new paradigm, the process of changing policies need to begin much sooner than was experienced in the implementation of the traditional life cycle model. The policy changes should be progressively modified to correspond to the advances in developing the new paradigm. This would allow the available rapid prototyping features to be utilized, thus making improvements on the current state of software development.

C. STRATEGIC GOALS FOR DoD'S IMPLEMENTATION OF NEW PARADIGM

DoD should establish strategic goals for the overall implementation of the rapid prototyping paradigm. These strategic goals should encompass the planning requirements prior to initial implementation and future enhancements of the paradigm. The strategic goals will be decomposed into near-term, short-term, and long-term goals in the following sections, which will explain in more detail how the paradigm should be implemented. These strategic goals provide the most critical actions that must be taken to insure implementation.

DoD must exert its authority now

DoD has to take the position that it intends to procure only software that is developed under the rapid prototyping paradigm. The intent of taking a strong position will result in an increase in effort by the software industry to develop the necessary support system. The stages should be developed to reflect its strong commitment to rapid prototyping.

DoD must establish intermediate Time-lines

Within the implementation stages described above, DoD must establish intermediate stages for meeting the proposed implementation period. These intermediate stages must include stages to produce completed conceptual rapid prototyping models, a prototype of the prototype support system, and a completed prototype support system environment. There could also be more intermediate stages to define the internal development of the prototyping support system environment. The process of selecting a model or a set of models could be commensurate with existing procurement procedures which include competitive contractual bidding.

Make policy changes incrementally

The policy changes should be made incrementally to keep up with the rapid prototyping features as they are developed, tested, and implemented. These incremental policy changes would serve several purposes and would decrease the overall implementation time. The incremental changes would force the software industry to transition to the new processes of software development and would provide the enhancements to the requirements validation process initially without waiting for the entire system to be completed. Another reason to change the policies incrementally is that the process of producing the formal regulations upon implementation will be reduced considerably. Rather than waiting until the end to begin production of the formal regulations, the major components of the regulations will already be completed and would only require integration into the final formal regulations.

Continue funding research for future generations of rapid prototyping

Rapid prototyping will continue to evolve as advances in technology are made. Current technology limits which methodologies that can be modeled and

implemented. Even though it is recommended that DoD establish stages for the initial implementation of rapid prototyping, it should not be construed that the commitment should stop at that initial implementation. The eventual modeling and implementation of such methodologies as the automated software synthesis methodology is just as important as the initial implementation of the rapid throwaway methodology. Therefore DoD needs to continue funding research efforts which would eventually produce the implementation of such an advanced rapid prototyping methodology.

These strategies are evolutionary. With advances in computer technology and continued research efforts, the strategies could easily apply to future generations of the rapid prototyping paradigm. The strategies could also be improved upon as required to make the implementation of the initial or future generations more efficient.

D. NEAR-TERM GOALS FOR DoD'S IMPLEMENTATION OF NEW PARADIGM

The near-term goals described below are all currently feasible, given current technology. The near-term goals should be able to be implemented within a five to seven year period.

Implement a rapid throwaway prototyping model

A model designed on the rapid throwaway methodology, such as the generic (SDME) model is capable of being implemented now. This goal should be viewed as very near-term, within a two year period. The lack of need for a prototyping support system would allow this rapid implementation. The implementation of this type of model would provide some instant enhancements to the current software development process, particularly in the requirements validation process. The greatest

impact would be the ease of transition from current software development processes, in contrast to jumping right into an evolutionary prototyping model.

Develop and implement an incremental prototyping model

The development of an incremental model is more complex and would require more time. It is conceivable that an incremental prototyping model could be developed and implemented near the outer bound of the goal period (eight to ten years). The experience gained from exposure to the rapid throwaway prototyping model should make the transition into the more detailed model easier. The environment to support an incremental prototyping model could be developed within this period of time since it is not very complex and is achievable now, given current technology.

Initiate prototyping tools testing and evaluation

There are sufficient prototypes of tools being developed currently to allow for initial testing and evaluation. This process needs to be formally defined and documented to insure that the tools will support both near-term and short-term goals. The process of testing and evaluating the prototyping tools will not be completed in the near-term , but the process should be initiated if short-term goals are to be me:

Develop a prototyping language

The prototyping language, which is necessary to support the evolutionary and reusable software components methodologies needs to be developed during this goal period in order to meet short-term goals. The prototyping language needs to be both specification-based and design-based to facilitate both the evolutionary and reusable software components methodologies. It is conceivable that the development of the language and the initial stages of testing and evaluation could be completed in the near-term .

Build reusable software component library

The construction of the reusable software component library will require a significant effort and will consume many years to complete. The design of the library structure needs to be defined in the very near-term and the process of developing the components needs to start soon thereafter. DoD should place a constraint on the library design that it must be object-oriented and support efficient retrieval and management procedures. The major constraints on the construction of the components should be that they be written in Ada and that they support instantiation of control constraints . It is also essential that every component in the library have an associated formal specification and a measure of how thoroughly it has been tested or whether it has been proven correct. Without this information, designers cannot tell what the components can do or whether they are sufficiently reliable.

Monitor prototyping/CASE tools development

DoD must insure that the development of the prototyping tools is consistent with future goals . The persistent push to the edges of technology will ensure that future generations of the paradigm are implemented. This monitoring process includes not only new tools that are being developed, but also the enhancements to existing tools deemed necessary during the initial tools testing and evaluation process described earlier. This process is very important for enabling future implementations of rapid prototyping methodology-based models.

E. SHORT-TERM GOALS FOR DoD'S IMPLEMENTATION OF NEW PARADIGM

The short-term goals require either more intensive development process efforts or advances in technology which exceed the near-term bounds. The short-term goals should be implemented within a fifteen to eighteen year period.

Evaluate incremental prototyping model

Prior to implementation of a more advanced rapid prototyping model, an evaluation of an already implemented model needs to be conducted. This evaluation process is important, since there may be some design flaws that require correction in the design of new models. If known or existing defects are not corrected early in the evolutionary process of introducing more advanced rapid prototyping models, any potential enhancements will be lost through the existing defects. DoD must ensure that the evaluation of implemented models is conducted and that efficiency is optimized given existing technological constraints.

Develop and implement evolutionary prototyping model with reuse capabilities

The development and implementation of an evolutionary prototyping model should be the focus of attention in the short-term period. The evolutionary prototyping model, such as CAPS or IPS, needs to include the utilization of reusable software components. The need for the software industry to automate the coding process is critical, given the growing budgetary constraints. DoD must push the software industry to produce an evolutionary system that enhances both the requirements engineering and coding processes.

The evolutionary prototyping model is very important for the improvement of the maintenance process in future software development projects. Since the

maintenance costs represent the majority of overall costs, DoD must ensure that a rapid prototyping model that decreases maintenance costs is implemented as soon as technology allows. Thus, any evolutionary prototyping model that gets DoD approval for implementation, should be efficient enough to automate the maintenance effort and therefore drastically reduce the maintenance costs.

Procure prototyping support system environment

DoD should procure a prototyping support system environment that will support an evolutionary rapid prototyping process. The procurement of such a system would facilitate DoD production of large real-time systems and future retrofitting of existing systems that were not developed under the rapid prototyping paradigm. The prototyping support system should be thoroughly tested and evaluated to ensure that it supports at least those criteria that were used to evaluate the models in Chapter IV.

Continue to build/maintain reusable software component library

The initial efforts explained in the description of building the component library in the presentation of near-term goals needs to be continued during this goal period. The evolution of the library must keep pace with the re-use requirements that newly developed and implemented rapid prototyping models require. This component construction process will continue to evolve throughout the short-term and most probably into the long-term.

The maintenance of the reusable software component library becomes paramount as the library grows. The library will undoubtedly expand to stretch the limits of both hardware storage and human memory. As the library expands, enhancements need to be made to improve efficiency in storage management as well as in supporting

the component retrieval processe in the evolutionary prototyping models. It is likely that reusable components will have to be initially generated from Ada code, then transformed into more general templates that can be used to automatically generate families of Ada programs to keep both computer and human memory requirements within practical limits.

As described in Chapter IV, CAPS could be implemented as the evolutionary prototyping model to build and maintain the reusable software component library. Some improvements in the areas of consistency and completeness checking need to be made to increase efficiency and automated detection. IPS is a viable candidate as well, if the definition of the post-design level development process is defined and meets the level of detail that was presented in the description of the design phase and if real-time consideration can be incorporated.

F. LONG-TERM GOALS FOR DoD'S IMPLEMENTATION OF NEW PARADIGM

The long-term goals are generally very complex and require dramatic advances in technology that would most likely exceed the upper bound of the short-term period. The long-term goals should be able to be implemented after the eighteen year mark.

Evaluate evolutionary prototyping model

This evaluation process is necessary for the same reasons stated in the short-term goal description of the incremental prototyping model. The evaluation of the implemented evolutionary prototyping model is even more appropriate, since the projected implementation of the next generation of rapid prototyping model is so distant. Since the technology required to realistically implement the automated software synthesis methodology is so advanced that an evolutionary prototyping model will be

in existence for possibly as long as the traditional life cycle model will be. For this reason, the evaluation process is critical for the sake of efficient software development into the next century.

Develop and implement an automated software synthesis designed model

The automated software synthesis methodology represents the last generation of rapid prototyping methodologies, as currently defined. The methodology provides the optimal automated software development process which ultimately reflects the goals of the rapid prototyping paradigm. A model designed according to this methodology will need to be developed and implemented as technology allows. How far into the long-term period this technology will be available for design and implementation is not predictable at this point. All that is clear at this point is that a model designed after this methodology will not be available for implementation before the lower bound of this goal period.

Retrofit existing systems not developed under a rapid prototyping model

The cost benefits of developing and maintaining a software system make this goal a necessity. The costs of maintaining systems not developed under the evolutionary designed model are likely to exceed the total costs of developing a new system. A retrofitting process of existing systems should be less complicated than designing new systems. If the existing system is currently meeting the users requirements, then the process should be expedited somewhat. If the existing system requires enhancements, then the retrofitting process should also be easier. In each case, the user will be more familiar with the requirements and the designer already will have a facsimile of a prototype in the existing system.

Retrofit existing systems to execute with parallel processing

As technology becomes more advanced to allow parallel processing, the existing systems would require some retrofitting to allow for this enhancement to increase system efficiency. The real-time capabilities that parallel processing will provide should outweigh the costs associated with the retrofit process.

G. SUMMARY OF RECOMMENDATIONS

The recommendations of this chapter focus on DoD's need to exert its influence within the software industry to intensify the efforts to implement the rapid prototyping paradigm. The complex weapons systems, growing software demands, and the increasing software costs, provide the impetus for DoD to be a leader in support of introducing the new rapid prototyping paradigm.

The software development policies and regulations need to be modified incrementally to secure compliance and standard practices of software development in DoD. The new paradigm should be introduced in an incremental manner. This incremental evolution of the new paradigm should facilitate improvements in the requirements engineering process in the early stages and then move into automated software development as advances in technology allow.

The optimal methodology is automated software synthesis. But this methodology is realistically a very long-term goal. The evolutionary prototype methodology should represent the next generation of software life cycle model. Both CAPS and IPS are models that conceptually implement the evolutionary methodology. Some enhancements and more detailed definition of development processes need to be done to facilitate either of these models to be implemented as DoD standard life cycle models.

DoD must continue to fund research efforts in software engineering. The research should continue to push the limits of technology and find ways to make the software development process more fully automated.

VI. CONCLUSION

The traditional life cycle model has served the software industry well, but the opportunity to move into a more automated software development era is now present. Most of the existing problems in current software development practice can be corrected by the implementation of the new rapid prototyping paradigm.

The rapid prototyping paradigm will require a complex prototyping support system environment to facilitate the added automation. The design and development of the prototyping environment is not an easy task and will consume many man-years to be ready for implementation. The development of the prototyping tools independently of each other will delay a more detailed evaluation because of the dependency that the tools have on each other for execution. Most of the tools are capable of being developed now, with current technology, but the process is currently very "slow". The importance of getting the tools built , at least a prototype of the tools that will be executable, is magnified by the growing budgetary constraints that DoD is currently experiencing.

The survey and evaluation of the five rapid prototyping methodologies revealed a progressive description of how the new paradigm can evolve as technology is advanced. The methodologies range from those that can be implemented now (rapid throwaway) to a fully automated methodology (automated software synthesis) that is seen more as a long-term implementation goal. The initial implementation will target the persistent requirements engineering problems experienced in the traditional

life cycle model. Later implementations will automate the design and coding process, and provide enhancements to the expensive software maintenance efforts.

The three rapid prototyping models surveyed are, for the most part, are well defined. The CAPS and IPS models are evolutionary models that feature complex design-based prototyping languages and the reuse of software components. CAPS is the best defined model, but the lack of a complete implementation allows only a conceptual evaluation of the model at this point. IPS is well defined at the design phase, but the post-design phase is not well-developed at this time. However, the IPS model has accomplished some limited implementation of the design phase processes, and is currently undergoing testing and evaluation. The Generic (SDME) model is designed under the rapid throwaway methodology and is currently being implemented. The Generic Model is merely an integration of the principles of the new paradigm and the traditional life cycle model. The evaluation of these models revealed that some additional research is required, particularly in the areas of consistency and completeness checking and in automating maintenance.

DoD has long played a major role in the software industry. By funding research which has consistently pushed the limits of technology, DoD has exerted its influence on the software industry to move into the rapid prototyping era of software development. Although the recent research efforts and delayed policy implementations portray a reluctance to act, DoD's recent commitment to Ada and establishment of policies regarding software development reveal a bolder commitment to software engineering. DoD has a great need to insure that the rapid prototyping paradigm is implemented, given the persistent problems in the requirements engineering processes and growing software costs. The strategic goals described in Chapter V,

along with the near-term, short-term, and long-term goals should facilitate some much needed changes in current software development practices. Since DoD has so much to gain by implementing the new paradigm, it is clear that DoD has to take a leading role in pushing the software industry to expedite its implementation.

LIST OF REFERENCES

1. Ramamoorthy, C., Prakash, A., Tsai, W., and Usada, Y., "Software Engineering: Problems and Perspectives", *IEEE Software*, pp. 191-209, November 1984.

2. Janson, D., *A Static Scheduler For The Computer Aided Prototyping System: An Implementation Guide*, M.S. Thesis, Naval Postgraduate School, Monterey, CA, September 1988.

3. Booch, G., *Software Engineering With Ada*, 2nd ed., Benjamin/Cummings Publishing Co., Menlo Park, CA, 1987.

4. Boehm, B.W., "A Spiral Model of Software Development and Enhancement", *ACM Software Engineering Notes*, vol. 11, no.4, pp. 16-24, August 1986.

5. Davis, A., Bersoff, E., and Comer, E., "A Strategy for Comparing Alternative Software Development Life Cycle Models", *IEEETSE*, vol. 14, no. 10, pp. 1453-1461, October 1988.

6. Luqi, *Models For Evolutionary Software Development*, Technical Report NPS 52-89-055, Computer Science Department, Naval Postgraduate School, Monterey, CA, August 1989.

7. Bersoff, E., Gregor, B., and Davis, A., *Alternative Life Cycle Models*, BTG Inc., Vienna, VA, 1988.

8. Luqi and Berzins, V., "Rapidly Prototyping Real-Time Systems", *IEEE Software*, pp. 25-36, September 1988.

9. "The American Heritage Dictionary of the English Language", Houghton Mifflin Co., Boston, MA, 1978.

10. Luqi, *Execution of Real Time Prototypes*, Technical Report NPS 52-87-012, Computer Science Department, Naval Postgraduate School, Monterey, CA, 1987.

11. Brice, L, "Rapid Prototyping Matches System To User Needs", *Computerworld*, p. 8, August 26, 1985.

12. Schott, F. and Olson, M., "Driving For Normalcy", *Datamation,* pp. 68-76, May 1988.

13. Berzins, V. and Luqi, *Languages for Specification, Design, and Prototyping*, Technical Report NPS 52-88-038, Computer Science Department, Naval Postgraduate School, Monterey, CA, September 1988.

14. Luqi, "Specification Languages in Computer-Aided Software Engineering", *in Proceedings of IEEE Systems Design and Networks Conference,* Santa Clara, CA, pp. 27-34, April 1988.

15. Lempp, P. and Ranier, A., "System Development Support Environments", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering,* Cambridge, MA, pp. 50-55, May 1987.

16. Yau, S., Nicholl, R., Tsai, J., and Liu, S., "An Integrated Life-Cycle Model for Software Maintenance", *IEEETSE,* vol. 14, no. 8, pp. 1128-1144, August 1988.

17. Luqi, *Computer Aided Maintenance of Prototype Systems*, Technical Report NPS 52-88-037, Computer Science Department, Naval Postgraduate School, Monterey, CA, September 1988.

18. Bimson, K. and Burris, L., "Evolutionary Prototyping: Techniques For Structuring the Iterative Development of Knowledge-Based Systems", *Proceedings of the 23rd Annual Hawaii International Conference on System Sciences*, Kona, HI, pp. 211-219, January 1990.

19. Jordan, P., Keller, K., Tucker, R., and Vogel, D., "Software Storming, Combining Rapid Prototyping and Knowledge Engineering", *Computer,* pp. 39-48, May, 1989.

20. Yin, W. and Tanik, M., *DAA, A Prototype of an Integrated System (IPS) : Programmer's Reference Manual*, Technical Report 89-CSE-3, Department of Computer Science and Engineering, Southern Methodist University, Dallas, TX, February 1989.

21. Tyron, D., "A Generic Model of Systems Development and Several Traversal Strategies", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering,* vol. 2, Cambridge, MA, pp. 25.14-25.18, July 1988

22. Luqi, and Ketabachi, M., "A Computer-Aided Prototyping System", *IEEE Software,* vol. 5, no. 2, pp. 66-72, March 1988.

23. Luqi, "Software Evolution Via Rapid Prototyping", *IEEE Computer*, pp. 13-25, May 1989.

24. Tanik, M. and Yeh, R., "Rapid Prototyping in Software Development", *Computer*, vol. 22, no. 5, pp. 9-10, May 1989.

25. Yin, W. and Tanik, M., *DAA, A Prototype of an Integrated System (IPS) : User's Manual*, Technical Report 89-CSE-3, Department of Computer Science and Engineering, Southern Methodist University, Dallas, TX, February 1989.

26. Berzins, V. and LuQi, "Software Engineering with Abstractions: An Integrated Approach to Software Development using Ada", *Addison-Wesley*, 1990.

27. White, L., *The Development of a Rapid Prototyping Environment*, M.S. Thesis, Naval Postgraduate School, Monterey, CA, December 1990.

BIBLIOGRAPHY

Agresti, W., "What Are The New Paradigms", *New Paradigms For Software Development,* IEEE Computer Society Press, 1986.

Alford, M.W., *Software Requirements Engineering Methodology,* SREP Final Report, Vol. 1, TRW, Huntsville, AL, August 1977.

Bassett, P., "Unifying The Life-Cycle: CASEing Reusability", *Advanced Working Paper of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, May 1987.

Bassett, P., "Reusability in Software Design, Construction, and Maintenance", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering,* vol. 2, Cambridge, MA, pp. 29.3-29.4, July 1988.

Bell, T.E., "An Extendable Approach to Computer-Aided Software Requirements Engineering", *IEEETSE,* vol. 3, no. 1, pp. 49-60, January 1977.

Beregi, W.E., "Architecture Prototyping in The Software Engineering Environment", *IBM Systems Journal,* vol. 23, no. 1, pp. 4-18, 1984.

Bergland, G.D., "A Guided Tour of Program Design Methodologies", *Computer,* vol. 14, no. 10, pp. 13-37, October 1981.

Bergland, G.D. and Zave, P., "Guest Editors' Special Issue on Software Design Methods", *IEEETSE,* vol. SE-12, no. 2, pp. 185-191, February 1986.

Bernier, L., "User Requirements without Models", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering,* vol. 2, pp. 25.3-25.5, July 1988.

Berzins, V., *Object-Oriented Rapid Prototyping*, Technical Report NPS 52-88-044, Computer Science Department, Naval Postgraduate School, Monterey, CA, September 1988.

Bjoerner, D. and Jones, C., *Formal Specification and Software Development,* PRENTICE, 1982.

Blatt, S., "Rapid Software Prototyping Support Environments", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, pp. 192-193, May 1987.

Boar, B."Application Prototyping: A Life-Cycle Perspective", *Journal of Systems Management*, pp. 25-31, February 1986.

Bonasso, P. and Jordan, P., "A Software Storming Approach to Rapid Prototyping", *Proceedings of IEEE 22nd Annual Hawaii International Conference on System Science*, Kona, HI, pp. 368-376, January 1989.

Brackett, J., "The Potential of Executable Models During Requirements Specification", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, pp. 350-351, May 1987.

Burstall, R.M. and Goguen, J.A., "Putting Theories Together to Make Specifications", *Proceedings of 5th International Joint Conference on Artificial Intelligence*, Cambridge, MA, pp. 1045-1058, 1977.

Carasik, B., "Thinking About Thinking About the Software Factory of the Future", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering*, vol. 2, Cambridge, MA, pp. 25.6-25.9, July 1988.

Cieslak, R., Fawaz, A., Sachs, S., Varaiya, P., Warland, J., and Li, A., "The Programmable Network Prototyping System", *IEEE Software*, pp. 64-74, May 1989.

Clapp, J., "Rapid Prototyping for Risk Management", *in IEEE COMPSAC '87*, Washington D.C.: Computer Society Press of the Institute of Electirical and Electronics Engineers, pp. 17-22, 1987.

Combelic, D., "User Experience with New Software Methods", *in National Computer Conference (AFIPS)*, vol. 47, Montvale, NJ, pp. 631-633, 1978.

Connell, J. and Brice, L., "Rapid Prototyping", *Datamation*, vol. 30, pp. 93-100, 1977.

Cureton, B., "The Future of Unix As a Platform For C.A.S.E.", *Advanced Working Papapers of First International Workshop on Computer-Aided Software Engineering*, Campbridge, MA, pp. 211-215, May 1987.

Dod-STD-2167, *Defense System Software Development*, June 1985.

Durmer, J., "Tools Are Not Enough", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, pp. 160-167, May 1987.

Ferrans, J., "Facilitating Software Reuse Via Automated Libraries", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, pp. 500-502, May 1987.

Fickas, S., "Automating the Transformational Development of Software", *IEEETSE*, November 1985.

Gladden, G., "Stop the Life-Cycle, I Want to Get Off", *ACM Software Engineering Notes*, , vol. 7, no. 2, pp. 35-39, April 1982.

Goguen, J., "Reusing and Interconnecting Software Components", *Computer*, vol. 19, no. 2, pp. 16-28, February 1986.

Goguen, J. and Meseguer, J., "Rapid Prototyping in the OBJ Executable Specification Language", *Software Engineering Notes*, vol. 7, no. 5, pp. 75-84, December 1982.

Gomma, H., "The Impact of Rapid Prototyping on Specifying User Environments", *Software Engineering Notes*, vol. 8, no. 2, pp. 17-28, April 1983.

Gomma, H., "Prototypes--Keep Them or Throw Them Away?", *in Infotech State of the Art Report on Prototyping*, Pergamon Infotech Ltd.,Oxford, England, 1986.

Green, E., "Case and the Modeling Paradigm", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, p. 168, May 1987.

Hamilton, M and Zeldin, S., "The Functional Life Cycle Model and Its Automation", *Jounal of Systems and Software*, vol. 3, no. 1, pp. 25-62, March 1983.

Hatley, D. and Pirbhai, I., *Strategies for Real-Time System Specification*, Dorset House Publishing, New York, NY, 1988.

Henderson, P., "Functional Programming, Formal Specification, and Rapid Prototyping", *IEEETSE*, vol. SE-12, no. 2, pp. 241-250, February 1986.

Herndon, R. and Berzins, V., "The Realizable Benefits of a Language Prototyping Language", *IEEETSE*, vol. SE-14, no. 6, pp. 803-809, June 1988.

Hoare, C., "An Overview of Some Formal Methods for Program Design", *Computer*, vol. 20, no. 9, pp. 85-91, September 1987.

Hocking, D., "Defining Software For Software Engineering", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, p. 169, May 1987.

Ingle, A., Quigley-Lawrence, R., and Chan, Y., "Future of Large Software Development", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, pp. 170-174, May 1987.

Kemppainen, P. and Seppanen, V., "Augmentation of Real-Time CASE with a Total Reuse Scheme", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, pp. 29.5-29.9, July 1988.

Kerola, P. and Freeman, P., "A Comparison of Life Cycle Models", *in fifth IEEE International Conference on Software Engineering*, San Diego, CA, pp. 90-99, 1981.

Klinger, D., "Rapid Prototyping Revisited", *Datamation*, vol. 32, no. 20, pp. 131-132, October 1986.

Koegle, J., "Application of Enabling Technologies to Software Reusability", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, pp. 503-507, May 1987.

Lantz, K, "The Prototyping Methodology", *Technology Transfer Institute*, Santa Monica, CA, pp. 20-21, December 1988.

Levine, D., "Case '88 Position Paper", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering*, vol. 2, Cambridge, MA, pp. 25.10-25-11, July 1988.

Lewis, T. Handloser, F., Bose, S., and Yang, S., "Prototypes From Standard User Interface Management Systems", *IEEE Software, pp. 51-60, May 1988.*

Lubors, M., "Environmental Support for Reuse", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering*, vol. 2, Cambridge, MA, pp. 29.10-29.12, July 1988.

Luqi, *Knowledge Base Support For Rapid Prototyping*, Technical Report NPS 52-88-016, Computer Science Department, Naval Postgraduate School, Monterey, CA, July 1988.

Luqi, "Handling Timing Constraints in Rapid Prototyping", *in Proceedings of the 22nd Annual Hawaii International Conference on System Sciences*, Kona, HI, pp. 417-424, January 1989.

Luqi, *Rapid Prototyping Languages For Expert Systems*, Technical Report NPS 52-89-032, Computer Science Department, Naval Postgraduate School, Monterey, CA, March 1989.

Luqi, Berzins, V., and Yeh, R., "A Prototyping Language For Real-Time Software", *IEEETSE*, pp. 1409-1423, October 1988.

Luqi, Kraemer, B. and Berzins, V., *Software Analysis and Testing Through Prototyping*, Technical Report NPS 52-89-044, Computer Science Department, Naval Postgraduate School, Monterey, CA, March 1989.

Luqi and Lee, Y., *Interactive Control of Prototyping Process*, Technical Report NPS 52-89-014, Computer Science Department, Naval Postgraduate School, Monterey, CA, April 1989.

Martin, C., "Heirarchical Planning For Evolution of Large Information Systems", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering*, vol. 2, Cambridge, MA, pp. 25.12-25.13, July 1988.

McCracken, D. and Jackson, M., "Life Cycle Concept Considered Harmful", *ACM Software Engineering Notes*, vol. 7, no. 2, pp. 29-32, April 1982.

MIL-STD-1679A, *Weapon System Software Development*, October 1983.

Myer, B., "On Formalism in Specifications", *IEEE Software*, vol. 2, no. 1, pp. 6-26, January 1985.

Mostow, J. and Barley, M., "Automated Reuse of Design Plans", *in Proceedings of the 1987 International Conference on Engineering Design*, American Society of Mechanical Engineers, Boston, MA, pp. 632-647, August 1987.

Narayanaswamy, K. and Scacchi, W., "Maintaining Configurations of Evolving Software Systems", *IEEETSE*, vol. SE-13, no. 3, pp. 324-334, March 1987.

Naumann, J. and Jenkins, A., "Prototyping: The New Paradigm For Systems Development", *MIS Quarterly*, vol. 6, no. 3, September 1982.

Neighbors, J., "The Draco Approach to Constructing Software From Reusable Components", *IEEETSE*, May 1984.

Payne, R., "Integrative CASE Technologies With An Existing Software Development Methodology", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, pp. 179-180, May 1987.

Prieto-Diaz, R. and Freeman, P., "Classifying Software For Reusability", *IEEE Software*, vol. 4, no. 1, pp. 6-16, January 1987.

Schwaber, K, "Assessment of User Working Environment With CASE Tools", *Advanced Working Papers of First International Workshop on Computer-Aided Software Engineering*, Cambridge, MA, pp. 181-182, May 1987.

Stevens, W., "Data Flow Development Manager: A Technology For Reuse by Executing Data Flow Diagrams", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering*, vol. 2, Cambridge, MA, pp. 29.13-29.19, July 1988.

Tanik, M., "In Search of Silver Bullet", *in Proceedings of IEEE/ACM Fall Joint Computer Conference*, Dallas, TX, p. 686, November 1987.

Tsai, J., Aoyama, M., and Chang, Y., "Rapid Prototyping Using FRORL Language", *in Proceedings of COMPSAC '88*, pp. 410-417, October 1988.

Tyron, D., "A Generic Model of Systems Development and Several Traversal Strategies", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering*, vol. 2, Cambridge, MA, pp. 25.14-25.18, July 1988

U.S. General Accounting Office, "Contracting For Computer Software Development -- Serious Problems Require Management Attention To Avoid Wasting Additional Millions", *Report To The Congress of The United States*, November 1979.

Yadav, S., "Comparison of Analysis Techniques for Information Requirement Determination", *Communications of the ACM*, vol. 31, no. 9, pp. 1090-1096, September 1988.

Yeh, R., Roussopoulos, N., and Chu, B., "Management of Reusable Software", *in Proceedings of COMPCON*, pp. 311-320, September 1984.

Yeh, R. and Zave, P. "Specifying Software Requirements", *in Proceedings of the IEEE*, vol. 68, no. 9, pp. 1077-1085, September 1980.

Yin, W. and Tanik, M., "Reusability in the Real-Time Use of Ada", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering*, vol. 2, Cambridge, MA, pp. 29.20-29.28, July 1988.

Zultner, R., "A Framework For Software Engineering Models", *Advanced Working Papers of Second International Workshop on Computer-Aided Software Engineering*, vol. 2, Cambridge, MA, p. 274, July 1988.

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Dr. Lui Sha 1
Carnegie Mellon University
Software Engineering Institute
Department of Computer Science
Pittsburgh, PA 15260

COL C. Cox, USAF 1
JCS (J-8)
Nuclear Force Analysis Division
Pentagon
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Director, Tactical Technology Office
1400 Wilson Boulevard
Arlington, VA 2209-2308

Dr. R. M. Carroll (OP-01B2) 1
Chief of Naval Operations1
Washington, DC 20350

Dr. Aimram Yehudai 1
Tel Aviv University
School of Mathematical Sciences
Department of Computer Science
Tel Aviv, Israel 69978

Dr. Robert M. Balzer 1
USC-Information Sciences Institute
4676 Admiralty Way
Suite 1001
Marina del Ray, CA 90292-6695

Dr. Ted Lewis 1
Editor-in-Chief, IEEE Software
Oregon State University
Computer Science Department
Corvallis, OR 97331

Dr. R. T. Yeh
International Software Systems Inc. 1
12710 Research Boulevard, Suite 301
Austin, TX 78759

Dr. C. Green 1
Kestrel Institute
1801 Page Mill Road
Palo Alto, CA 94304

Prof. D. Berry 1
Department of Computer Science
University of California
Los Angelas, CA 90024

Director, Naval Telecommunications System Integration Center 1
NAVCOMMUNIT Washington
Washington, D.C. 20363-5110

Dr. Knudsen 1
Code PD50
Space and Naval Warfare Systems Command
Washington, D.C. 20363-5110

Ada Joint Program Office 1
OUSDRE(R&AT)
The Pentagon
Washington, D.C. 23030

CAPT A. Thompson 1
Naval Sea Systems Command
National Center #2, Suite 7N06
Washington, D.C. 22202

Dr. Peter Ng 1
New Jersey Institute of Technology
Computer Science Department
Newark, NJ 07102

Dr. Van Tilborg 1
Office of Naval Research
Computer Science Division, Code 1133
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. R. Wachter 1
Office of Naval Research
Computer Science Division, Code 1133
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. J. Smith, Code 1211 1
Office of Naval Research1
Applied Mathematics and Computer Science
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. R. Kieburtz 1
Oregon Graduate Center1
Portland (Beaverton)
Portland, OR 97005

Dr. M. Ketabchi 1
Santa Clara University
Department of Electrical Engineering and Computer Science
Santa Clara, CA 95053

Dr. L. Belady 1
Software Group, MCC
9430 Research Boulevard
Austin, TX 78759

Dr. Murat Tanik 1
Southern Methodist University
Computer Science and Engineering Department
Dallas, TX 75275

Dr. Ming Liu 1
The Ohio State University
Department of Computer and Information Science
2036 Neil Ave Mall
Columbus, OH 43210-1277

Mr. William E. Rzepka 1
U.S. Air Force Systems Command
Rome Air Development Center
RADC/COE
Griffis Air Force Base, NY 13441-5700

Dr. C.V. Ramamoorthy 1
University of California at Berkeley
Department of Electrical Engineering and Computer Science
Computer Science Division
Berkeley, CA 90024

Dr. Nancy Levenson 1
University of California at Irvine
Department of Computer and Information Science
Irvine, CA 92717

Dr. Mike Reiley 1
Fleet Combat Directional Systems Support Activity
San Diego, CA 92147-5081

Dr. William Howden 1
University of California at San Diego
Department of Computer Science
La Jolla, CA 92093

Dr. Earl Chavis (OP-162) 1
Chief of Naval Operations
Washington, DC 20350

Dr. Jane W. S. Liu 1
University of Illinois
Department of Computer Science
Urbana Champaign, IL 61801

Dr. Alan Hevner 1
University of Maryland
College of Business Management
Tydings Hall, Room 0137
College Park, MD 20742

Dr. Y. H. Chu 1
University of Maryland1
Computer Science Department
College Park, MD 20742

Dr. N. Roussapoulos 1
University of Maryland
Computer Science Department
College Park, MD 20742

Dr. Alfs Berztiss 1
University of Pittsburgh
Department of Computer Science
Pittsburgh, PA 15260

Dr. Al Mok 1
University of Texas at Austin
Computer Science Department
Austin, TX 78712

George Sumiall
US Army Headquarters
CECOM
AMSEL-RD-SE-AST-SE
Fort Monmouth, NJ 07703-5000 1

Mr. Joel Trimble
1211 South Fern Street, C107
Arlington, VA 22202 1

Linwood Sutton
Code 423
Naval Ocean Systems Center
San Diego, CA 92152-5000 1

Dr. Sherman Gee
Code 221
Office of Naval Technology
200 N. Quincy St.
Arlington, VA 22217 1

Dr. Mario Barbacci
Carnegie-Mellon University
Software Engineering Institute
Pittsburgh, PA 15213 1

Dr. Mark Kellner
Carnegie-Mellon University
Software Engineering Institute
Pittsburgh, PA 15213 1

Luqi
Code 52Lq
Computer Science Department
Naval Postgraduate School
Monterey, CA 93943 2

LCDR Rachel Griffin
Code CS/52
Computer Science Department
Naval Postgraduate School
Monterey, CA 93943 1

Captain Harrison D. Fountain
380D Bergin Dr.
Monterey, CA 94030